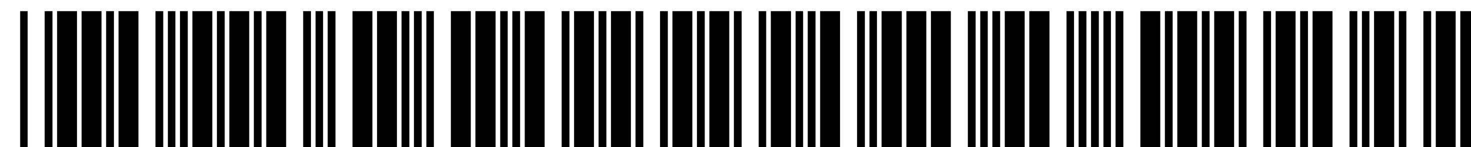

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Suzuki et al.

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(45) **Date of Patent: Jan. 30, 2018**

(54) **MIRROR DEVICE**

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(73) Assignee: **Gigaphoton Inc.**, Tochigi (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(51) **Int. Cl.**

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G02B 27/14	(2006.01)
G02B 26/06	(2006.01)
H01S 3/223	(2006.01)
H01S 3/23	(2006.01)

(52) **U.S. Cl.**

CPC ***H01S 3/0071*** (2013.01); ***G02B 7/182*** (2013.01); ***G02B 7/1815*** (2013.01); ***G02B 27/144*** (2013.01); ***H01S 3/1003*** (2013.01); ***H05G 2/008*** (2013.01); *G02B 26/06* (2013.01); *H01S 3/005* (2013.01); *H01S 3/2232* (2013.01); *H01S 3/2316* (2013.01); *H05G 2/003* (2013.01)

(58) **Field of Classification Search**

USPC .... 250/504 R; 359/819, 872

See application file for complete search history.

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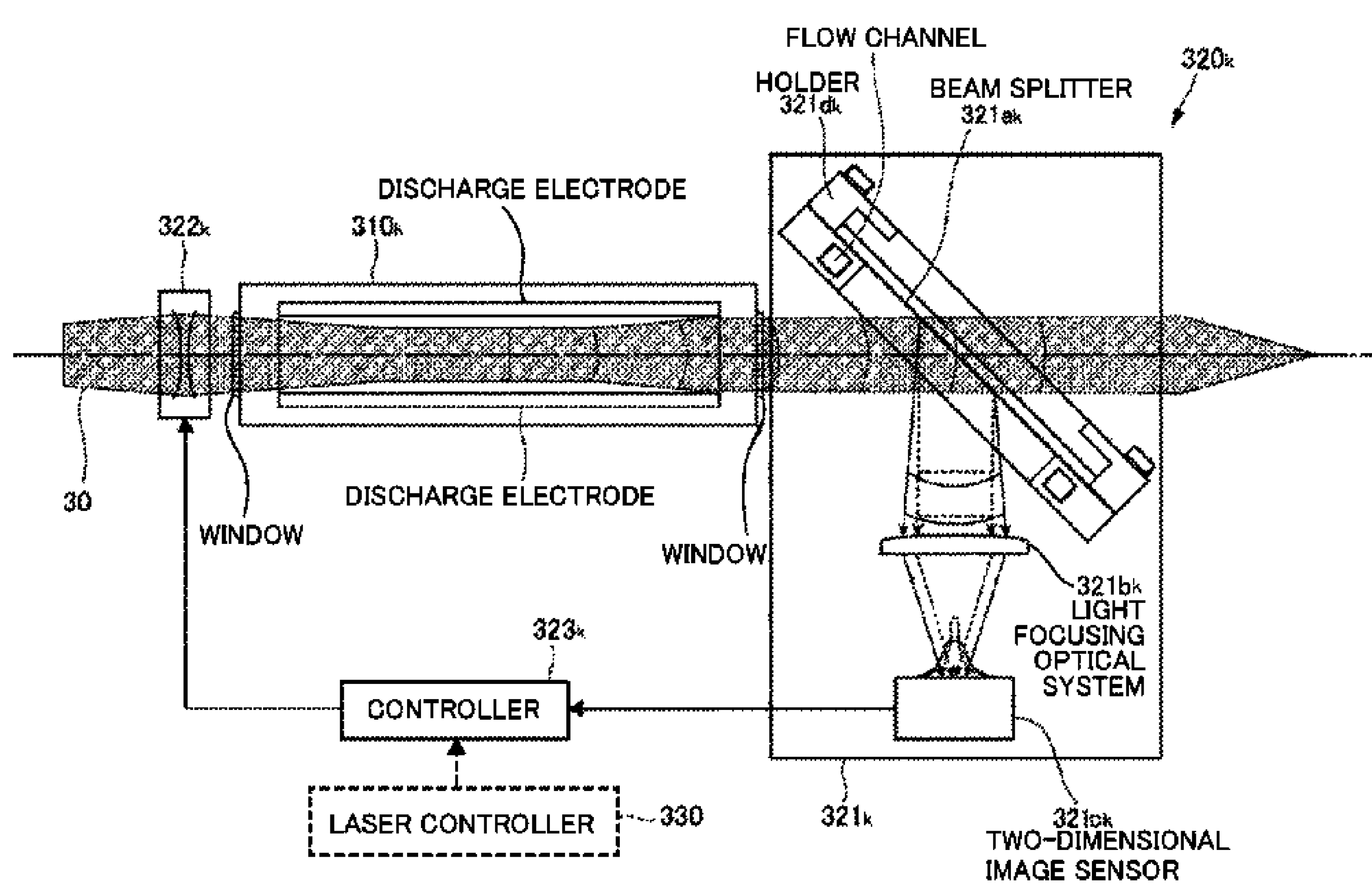
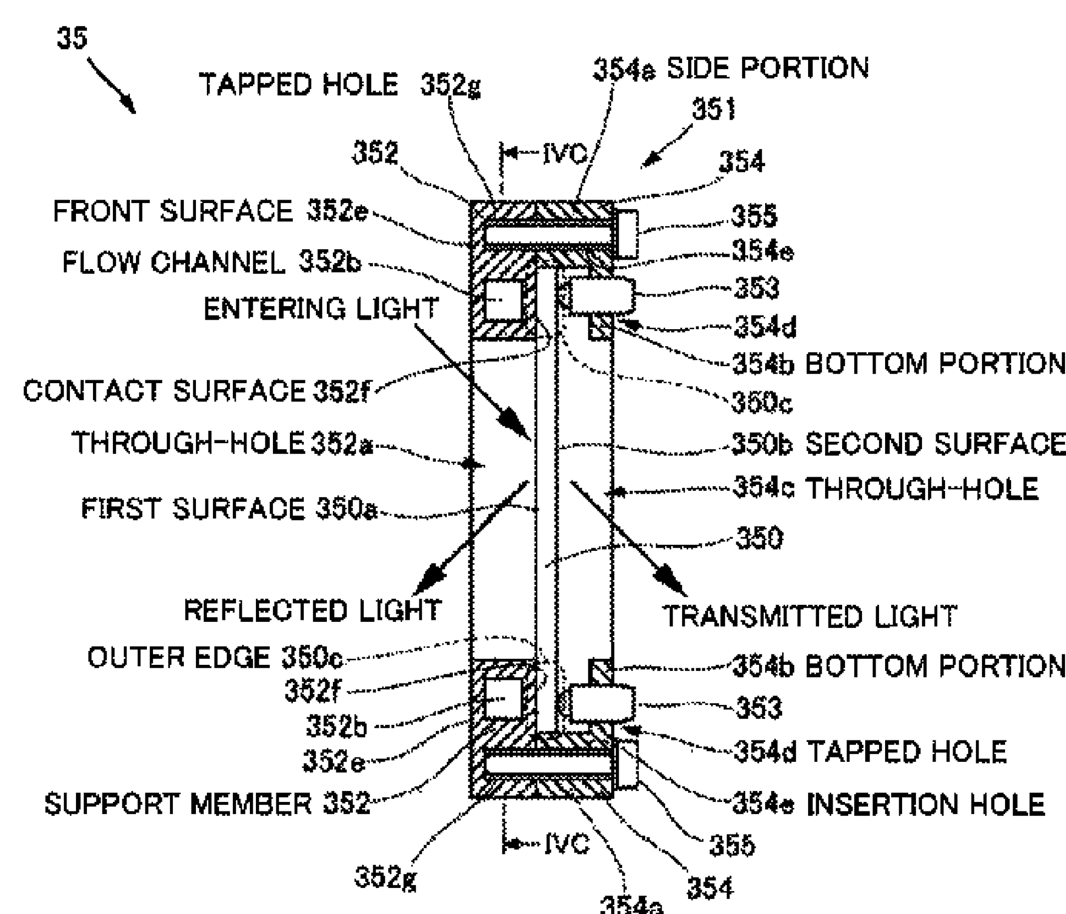
(57) **ABSTRACT**

A mirror device may include: an optical element configured to reflect part of a laser beam and transmit the other part of the laser beam therethrough; and a holder in surface contact with the optical element to hold the optical element. A flatness of a contact surface of the holder in contact with the optical element may be equal to or smaller than a flatness of the optical element.

9 Claims, 14 Drawing Sheets





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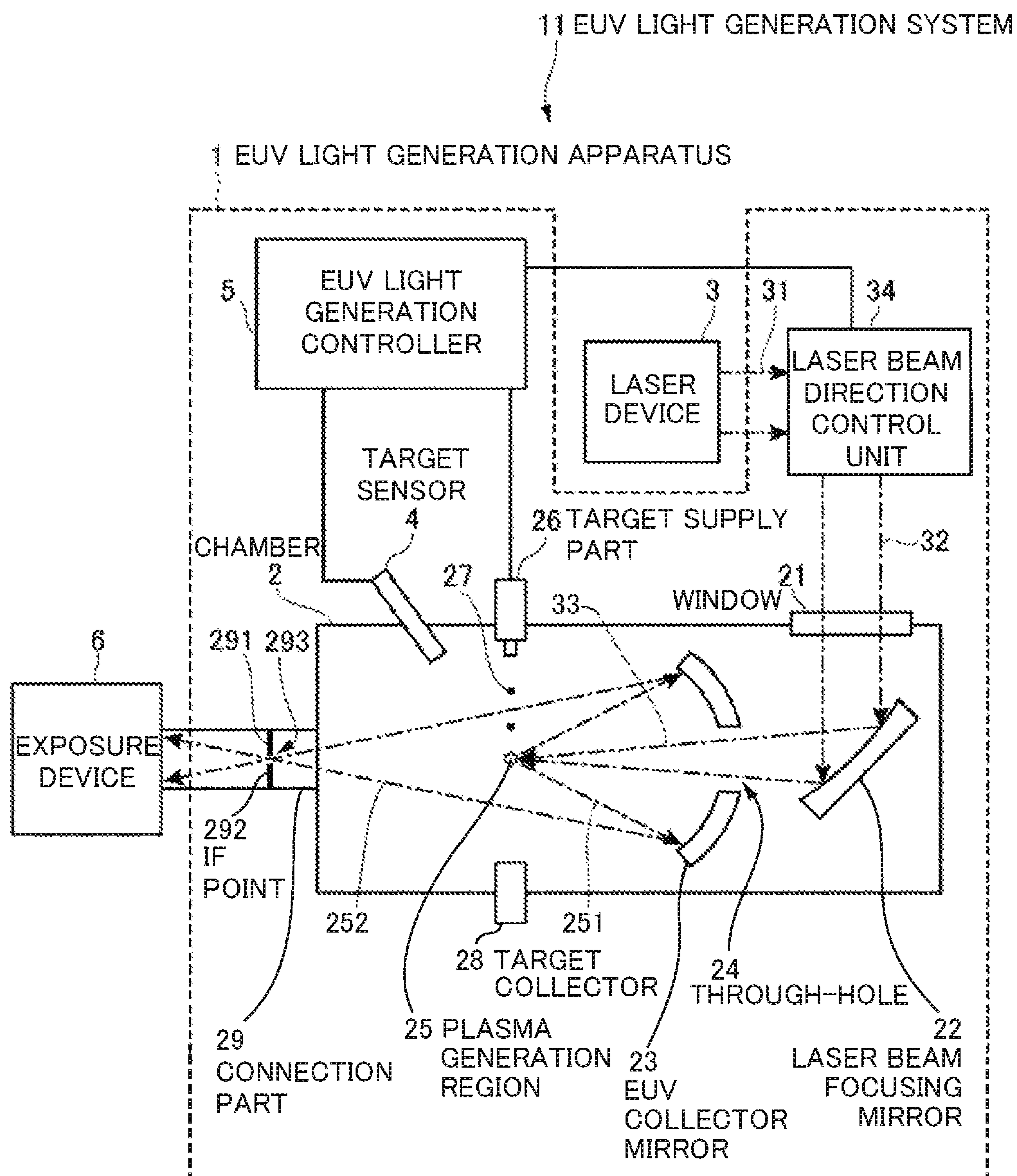


FIG.1

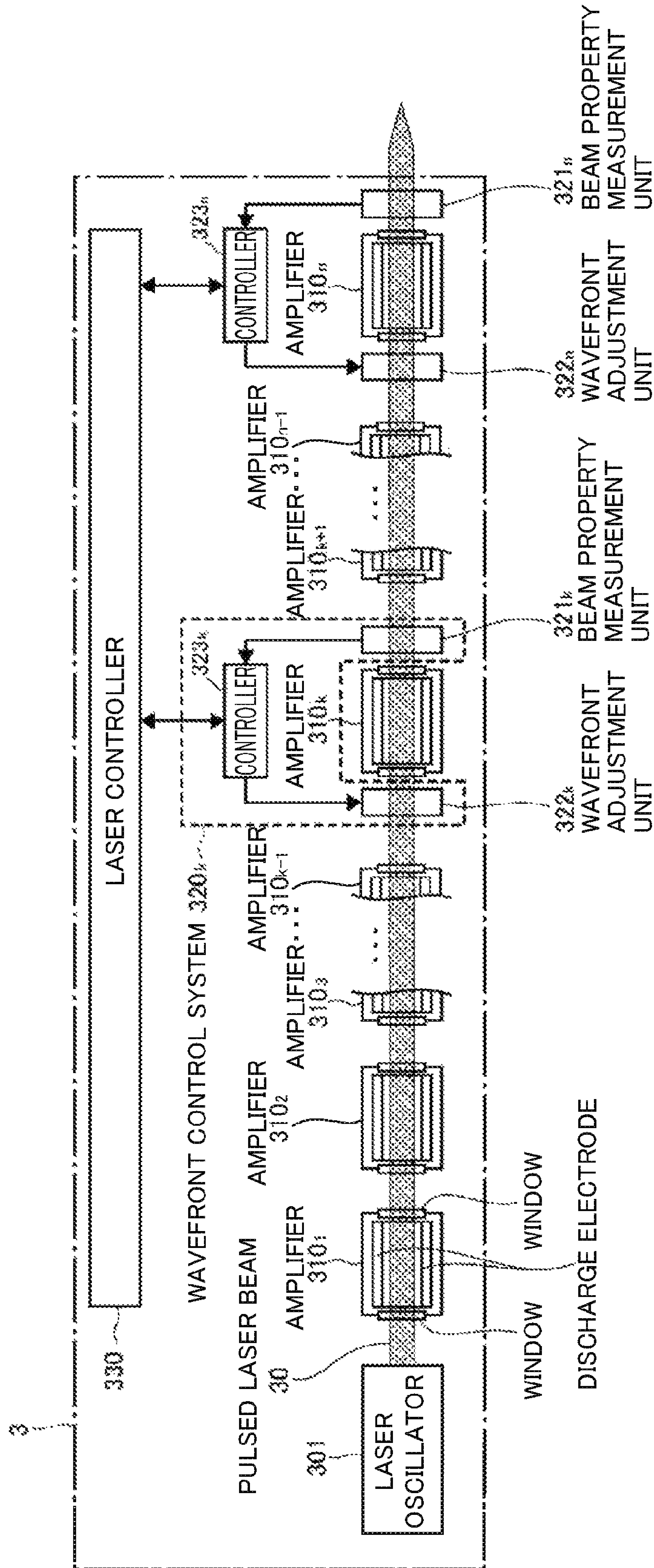


FIG.2

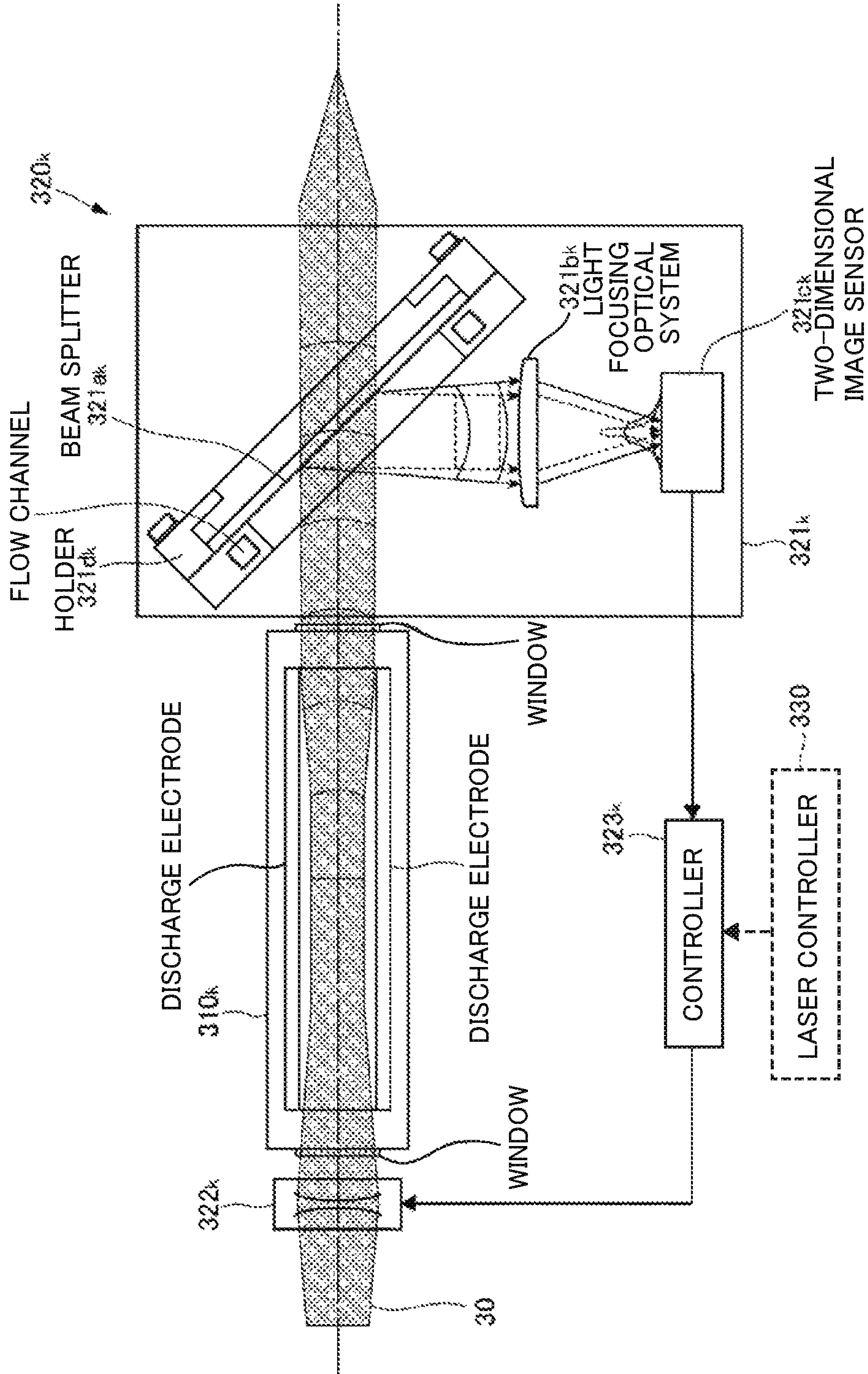


FIG.3

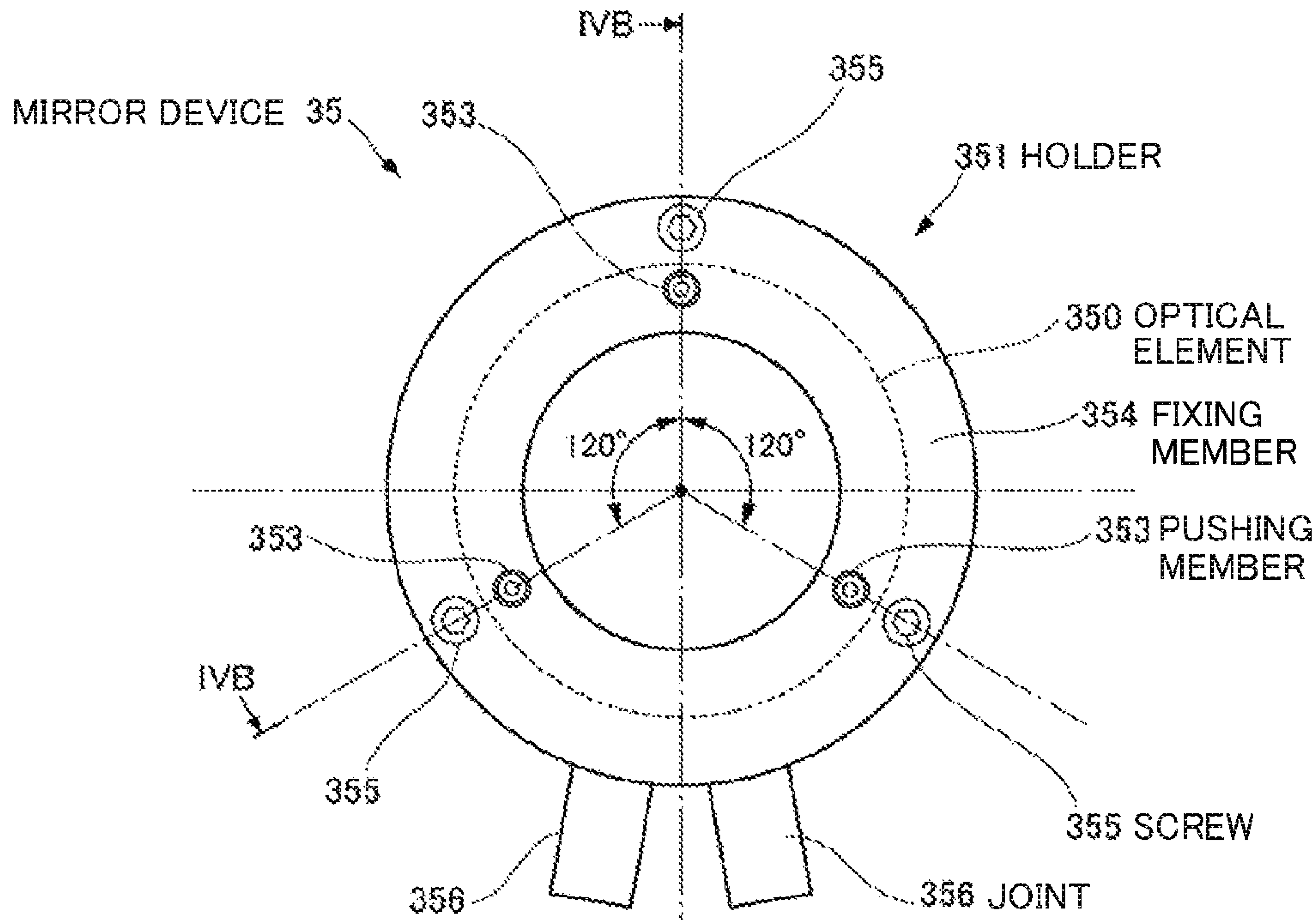


FIG.4 A

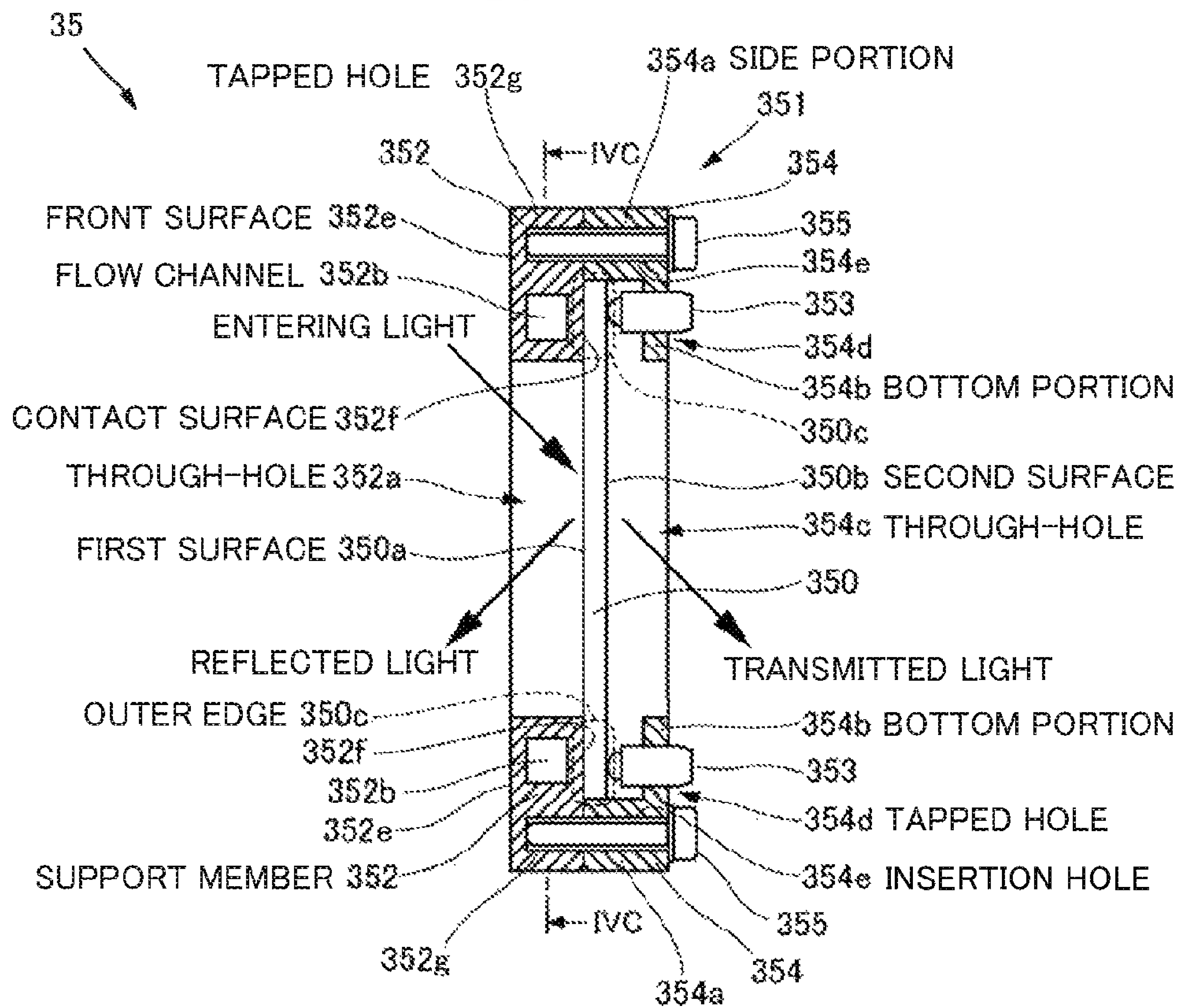


FIG.4 B

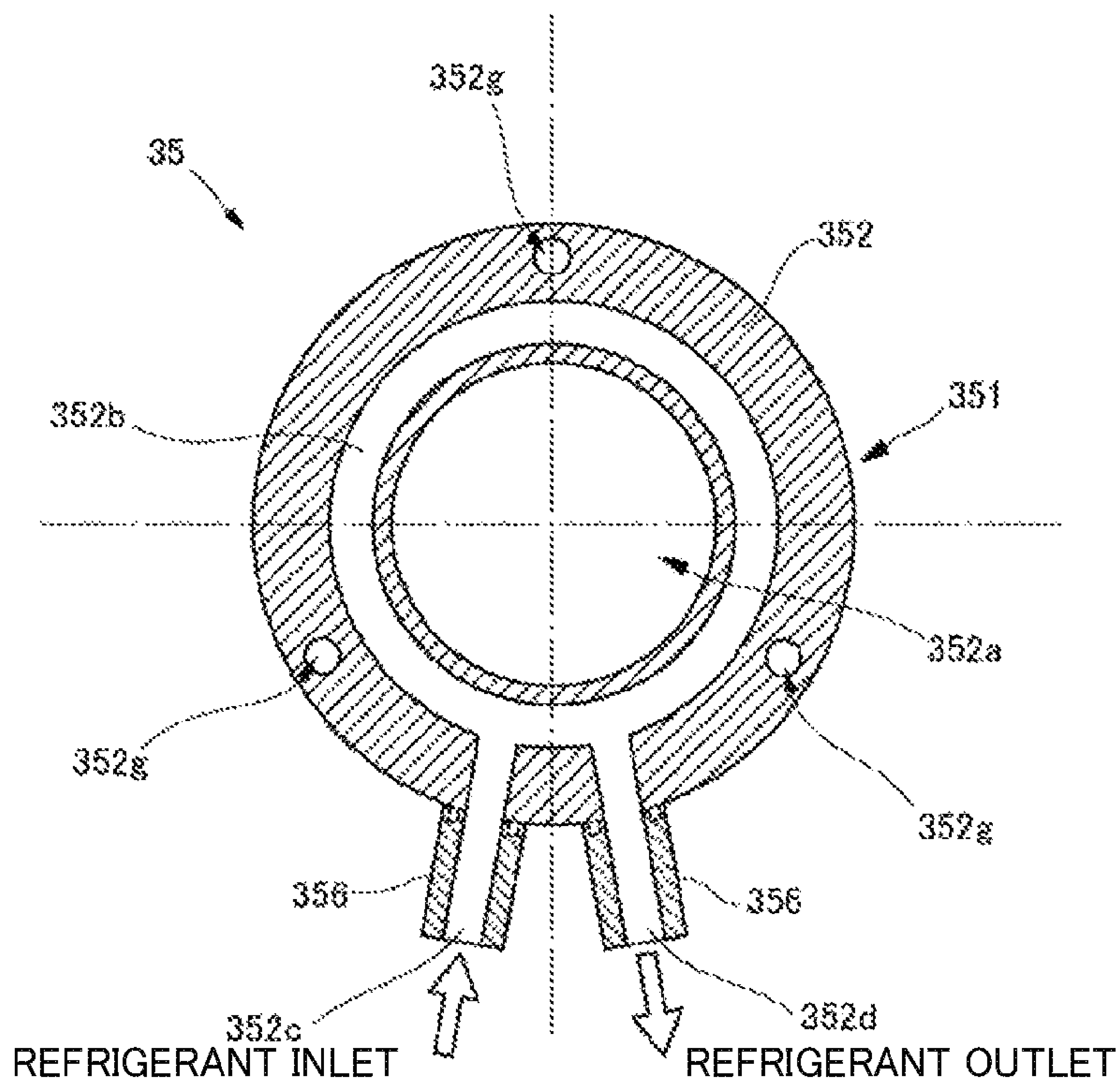


FIG.4 C

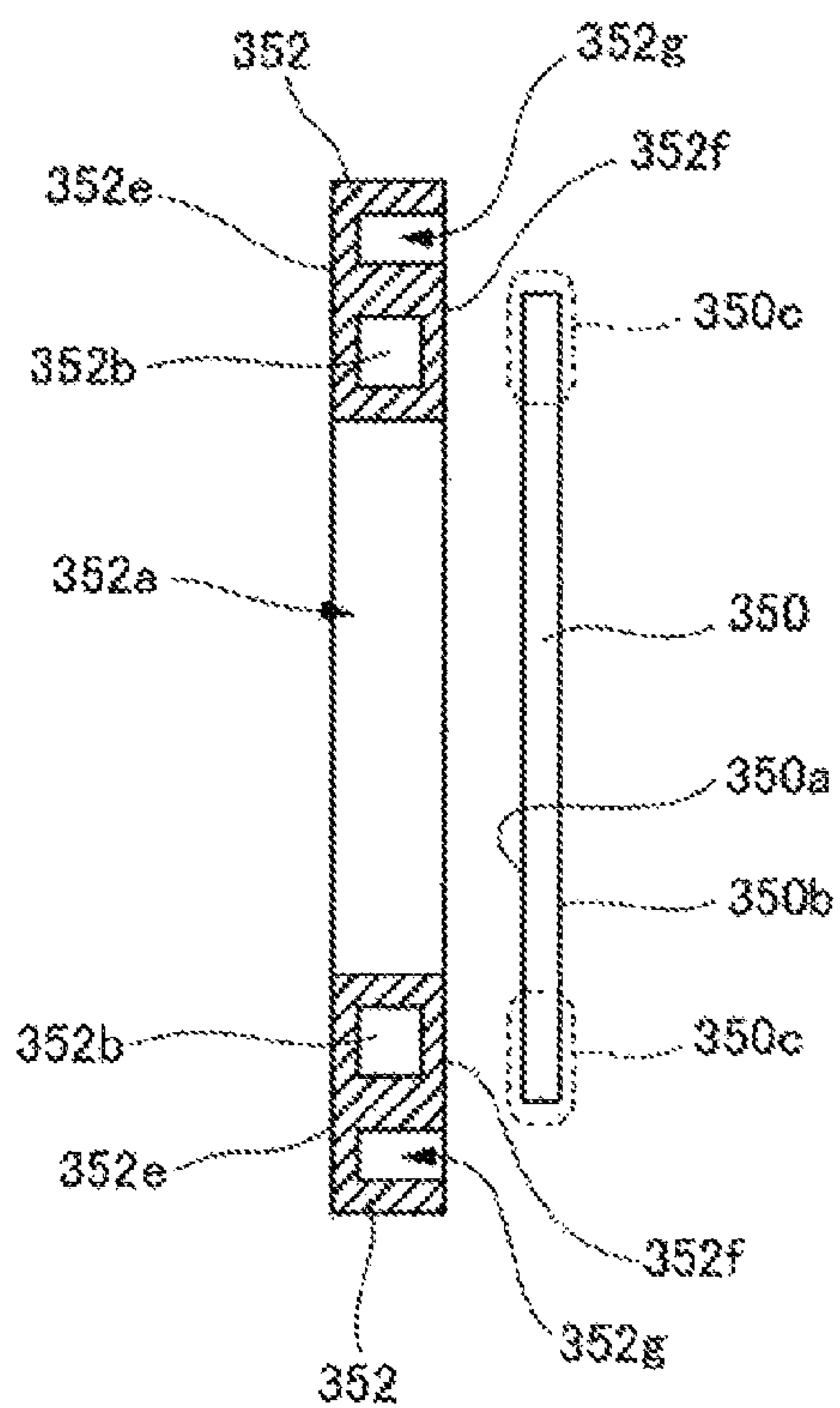


FIG.4 D

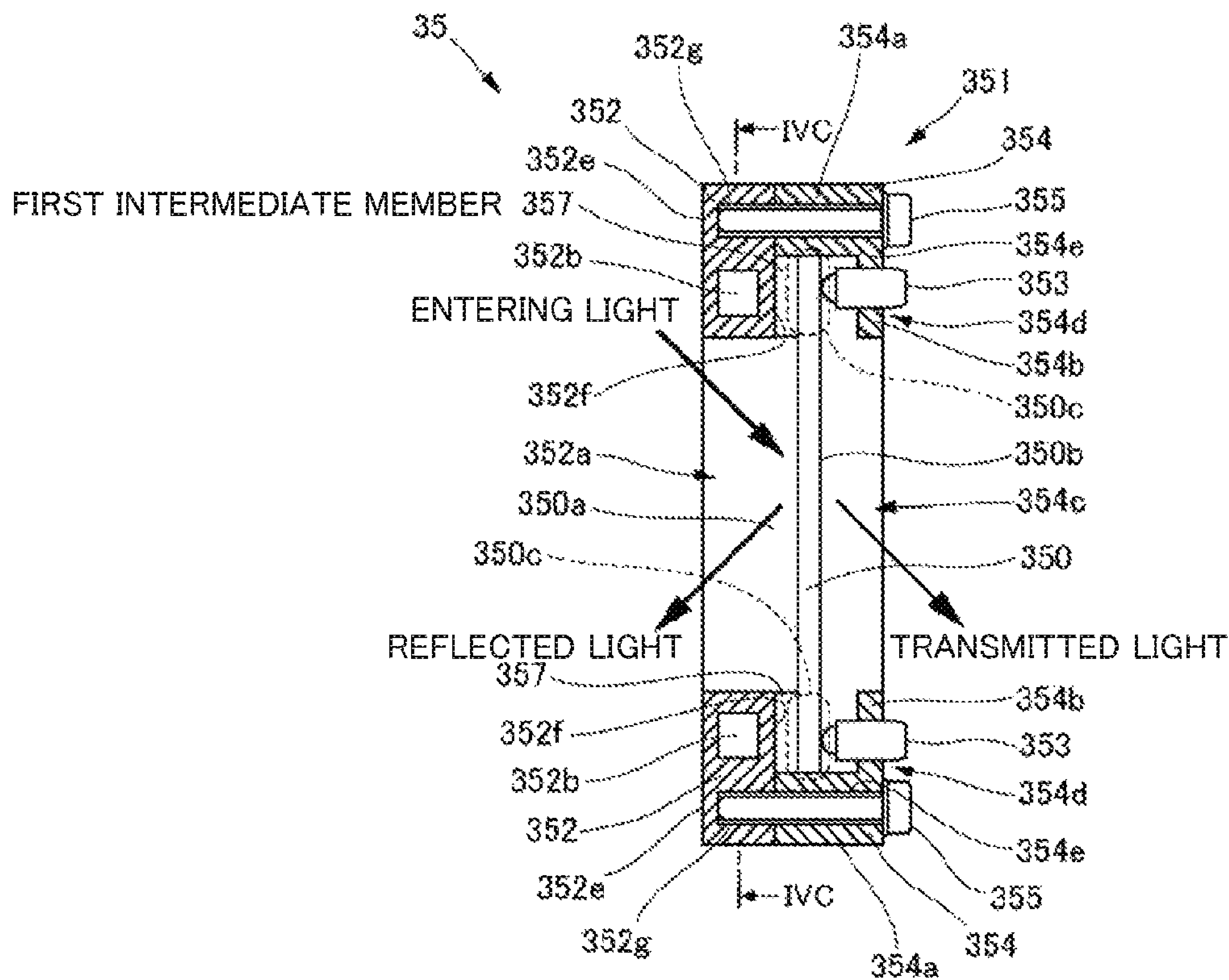


FIG.5 A

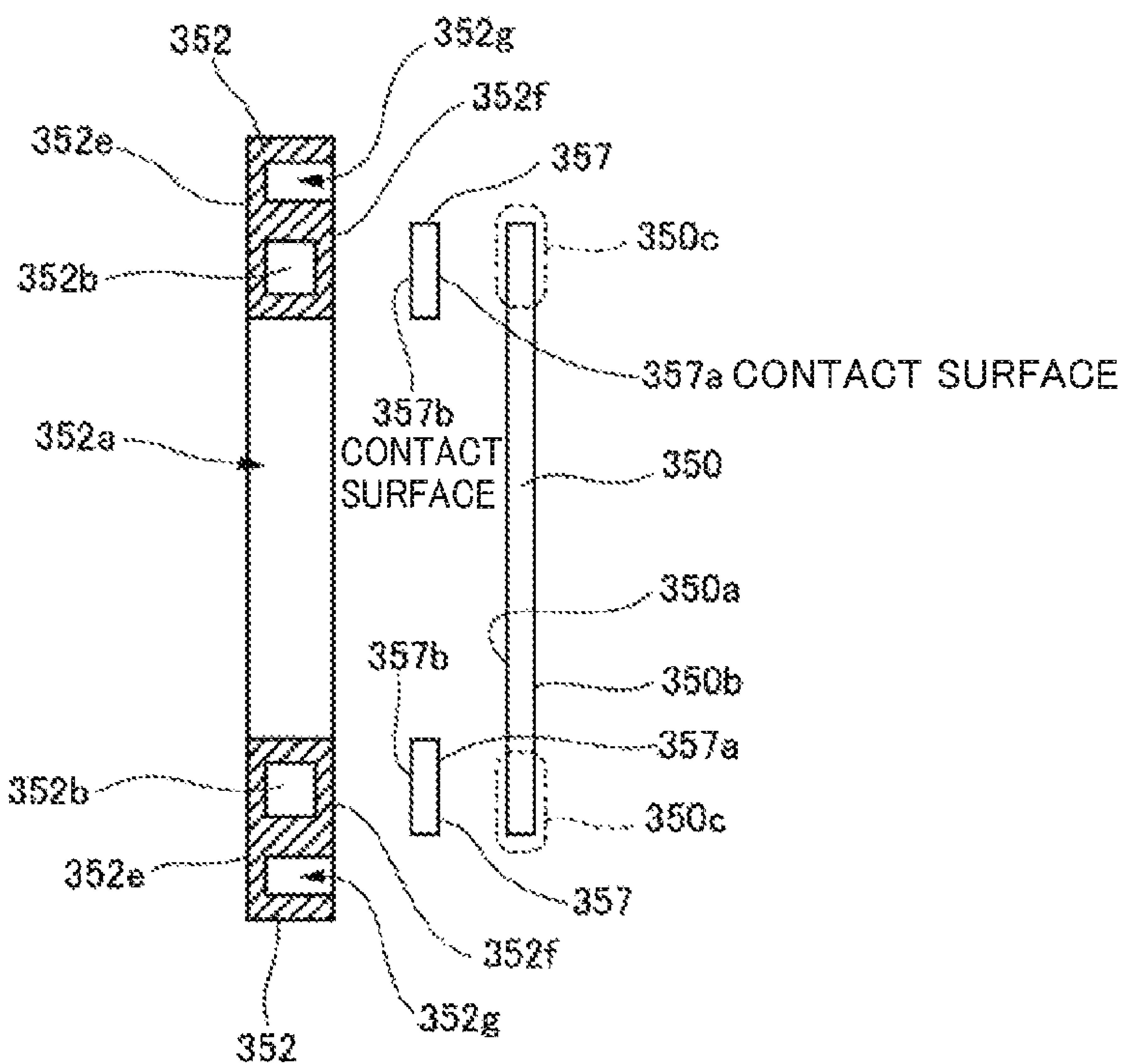


FIG.5 B

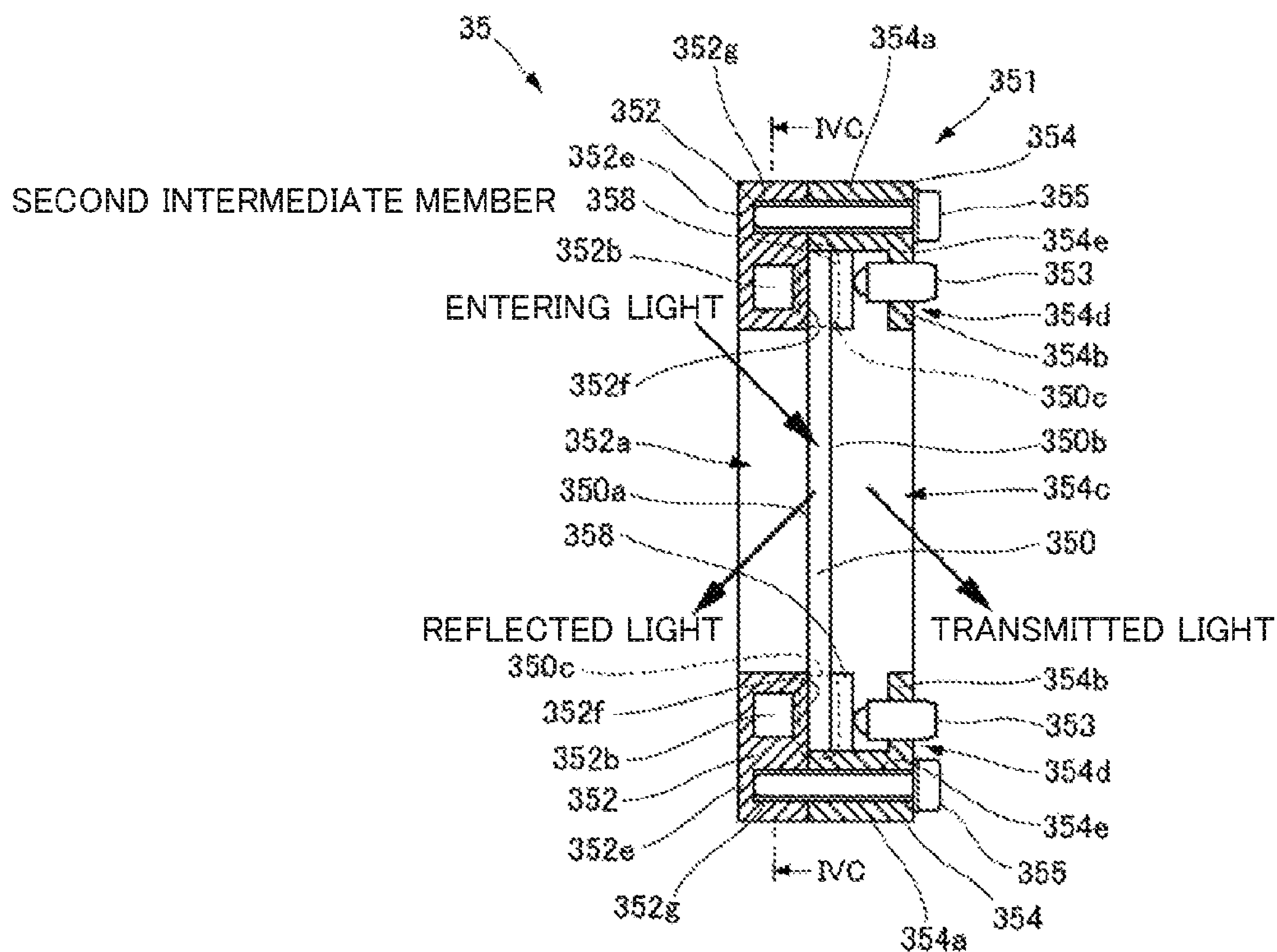


FIG.6 A

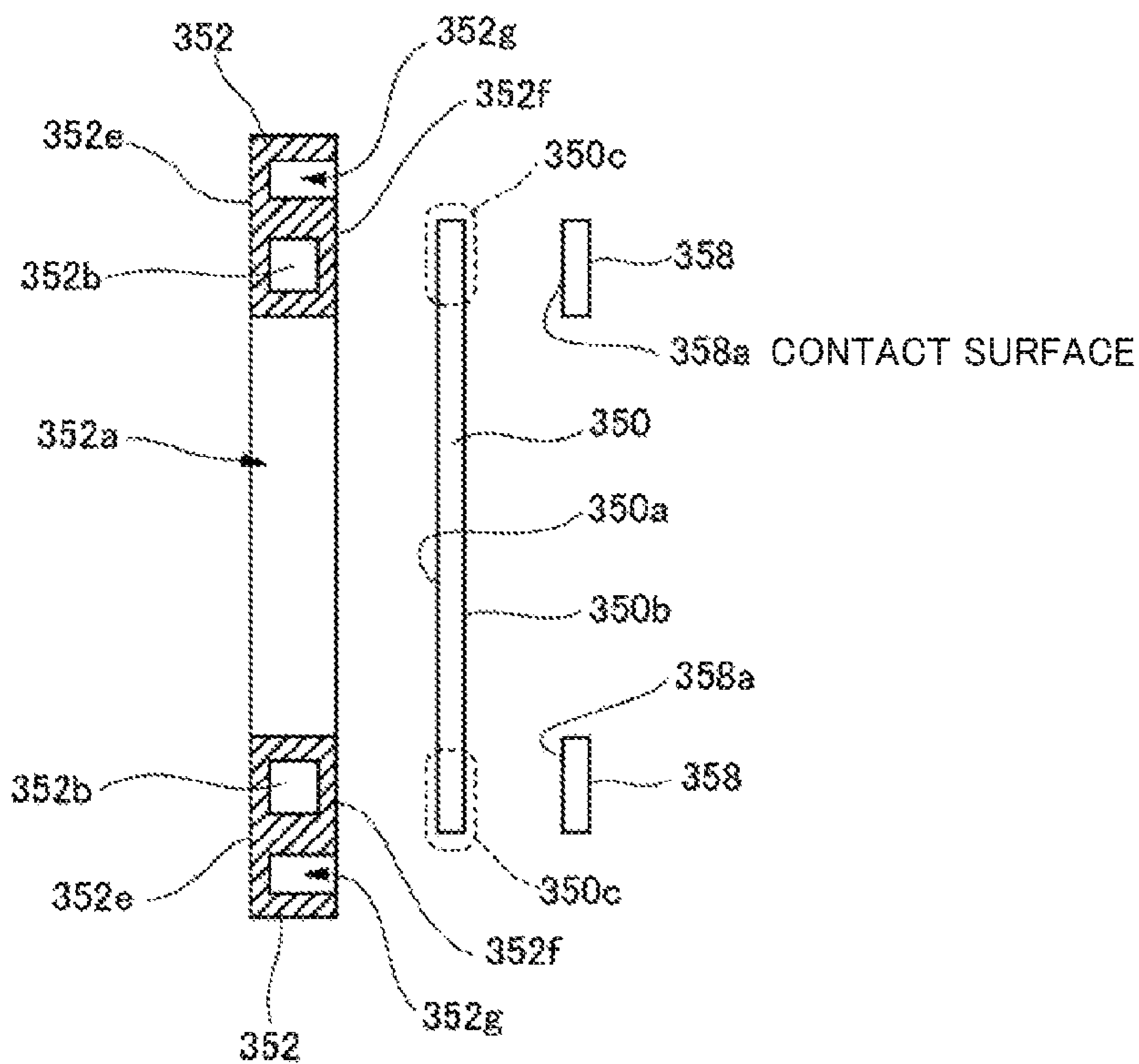


FIG.6 B

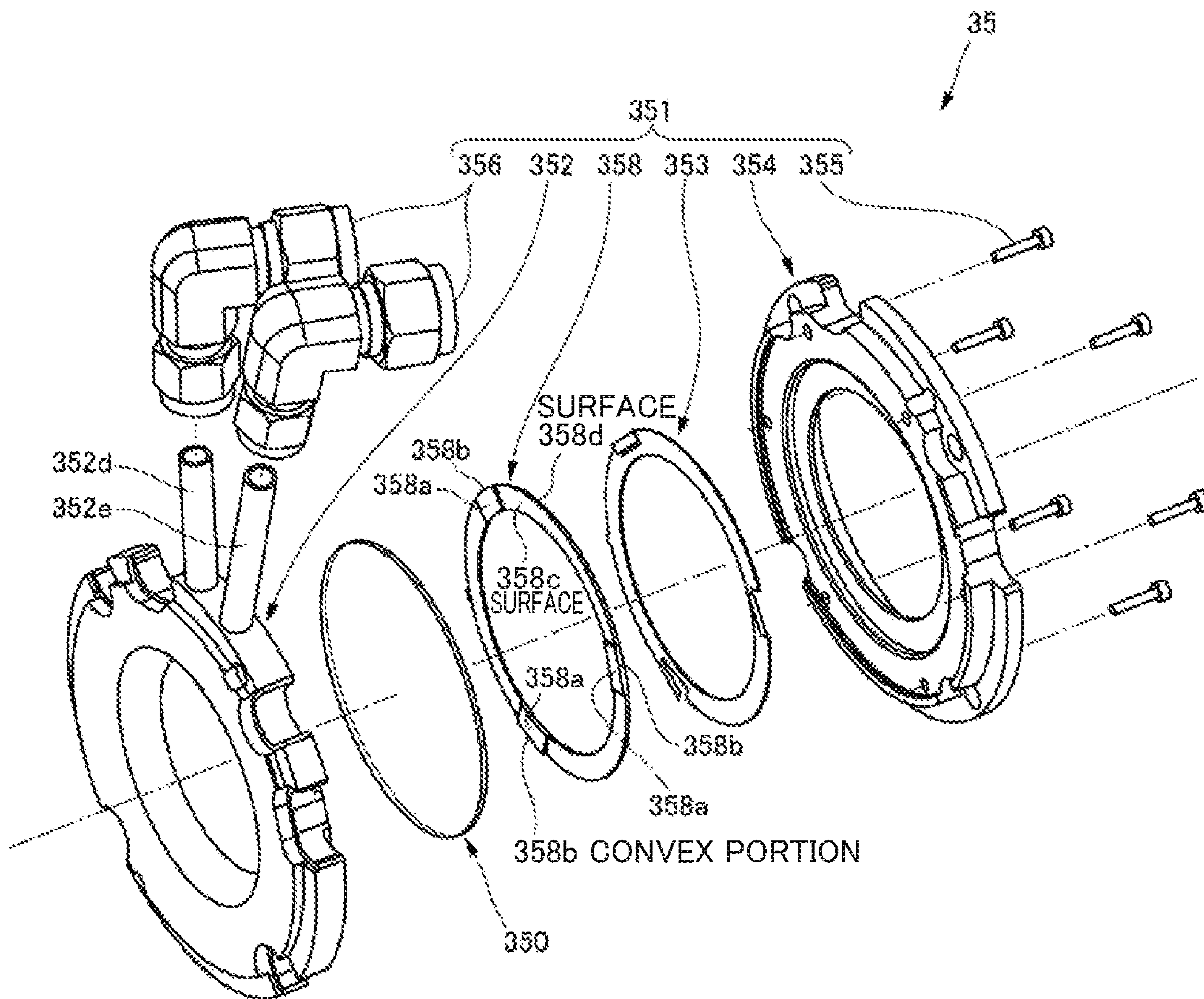


FIG.7

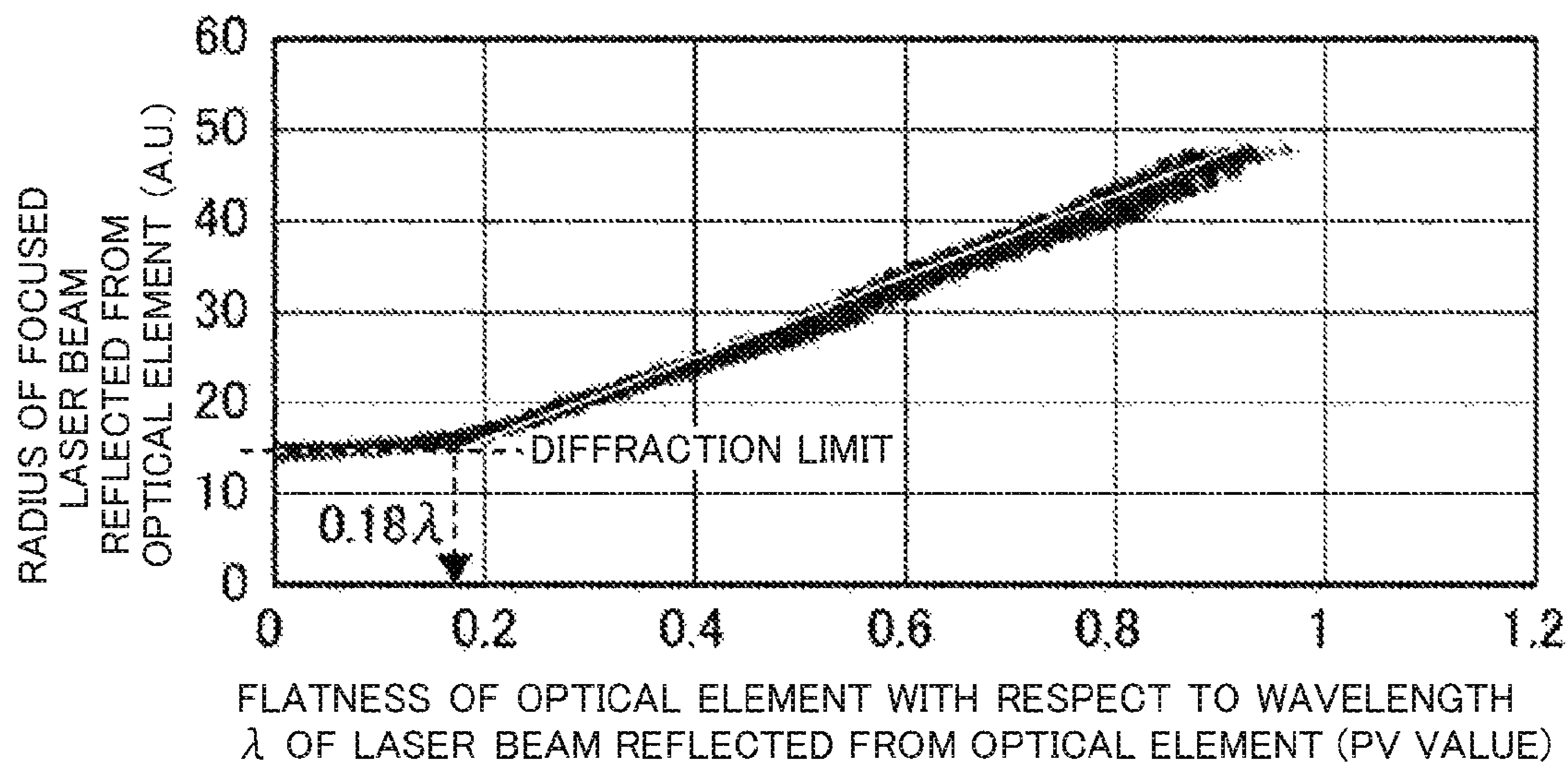


FIG.8

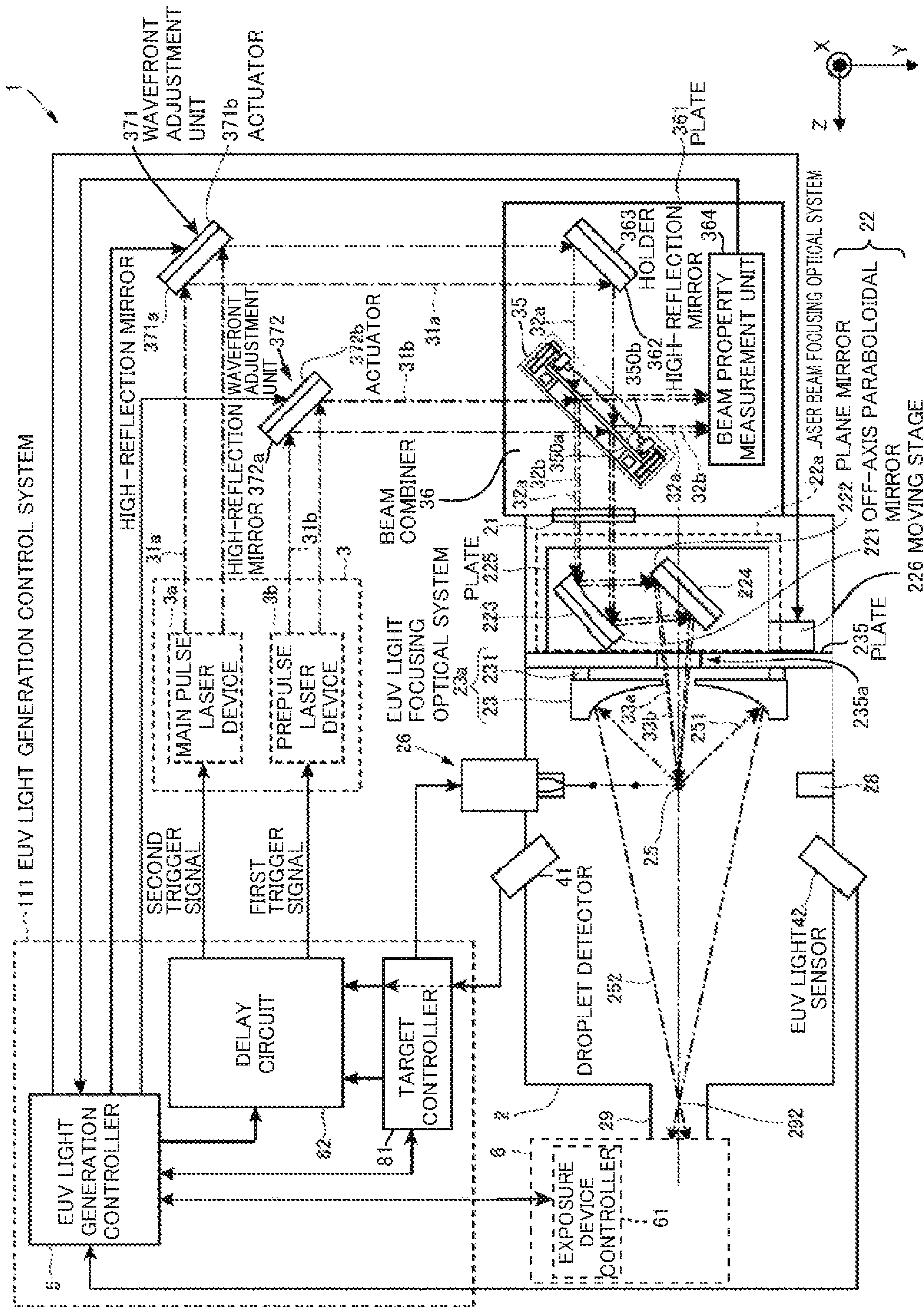


FIG.9

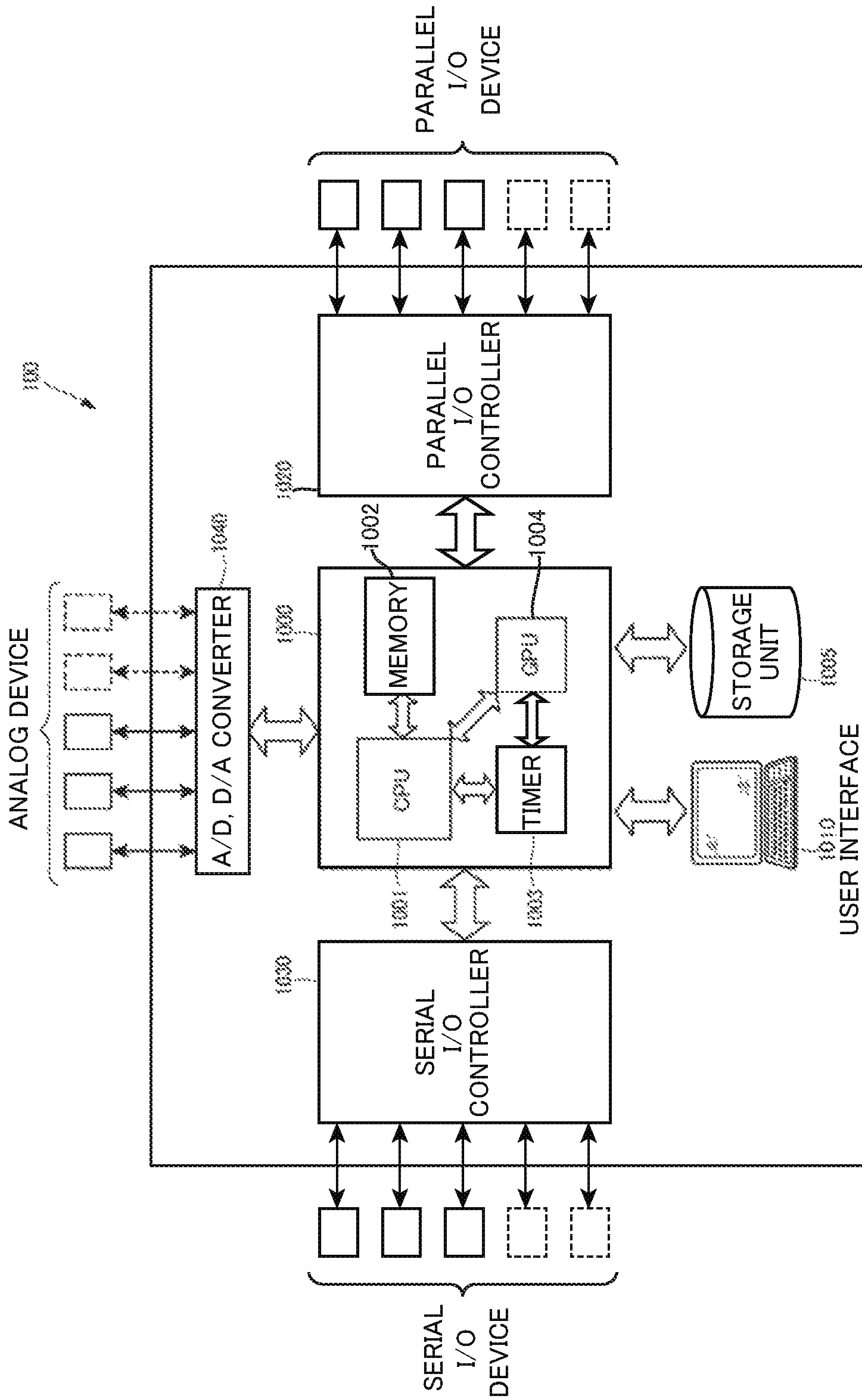


FIG. 10

FIG. 11 A

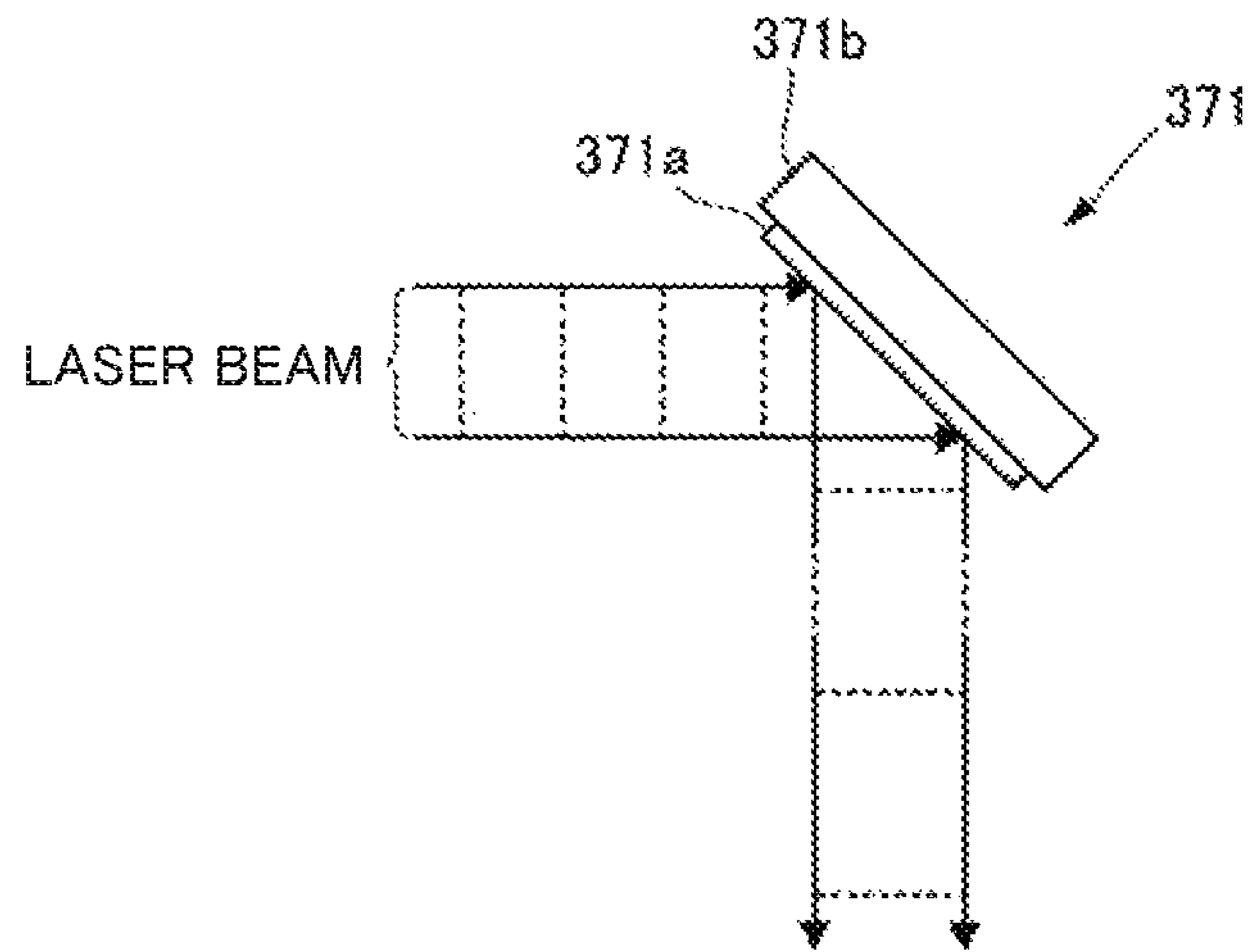


FIG. 11 B

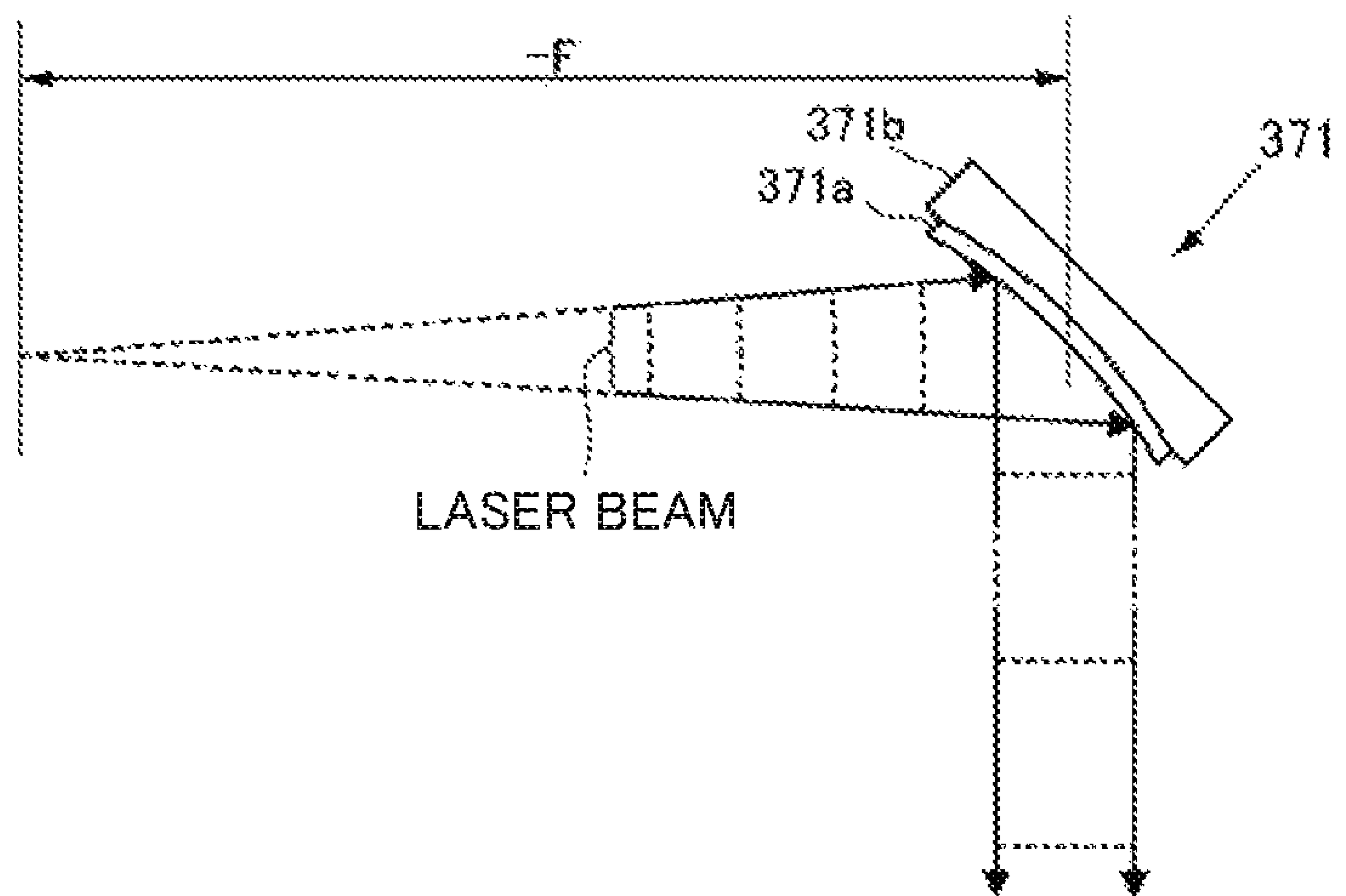
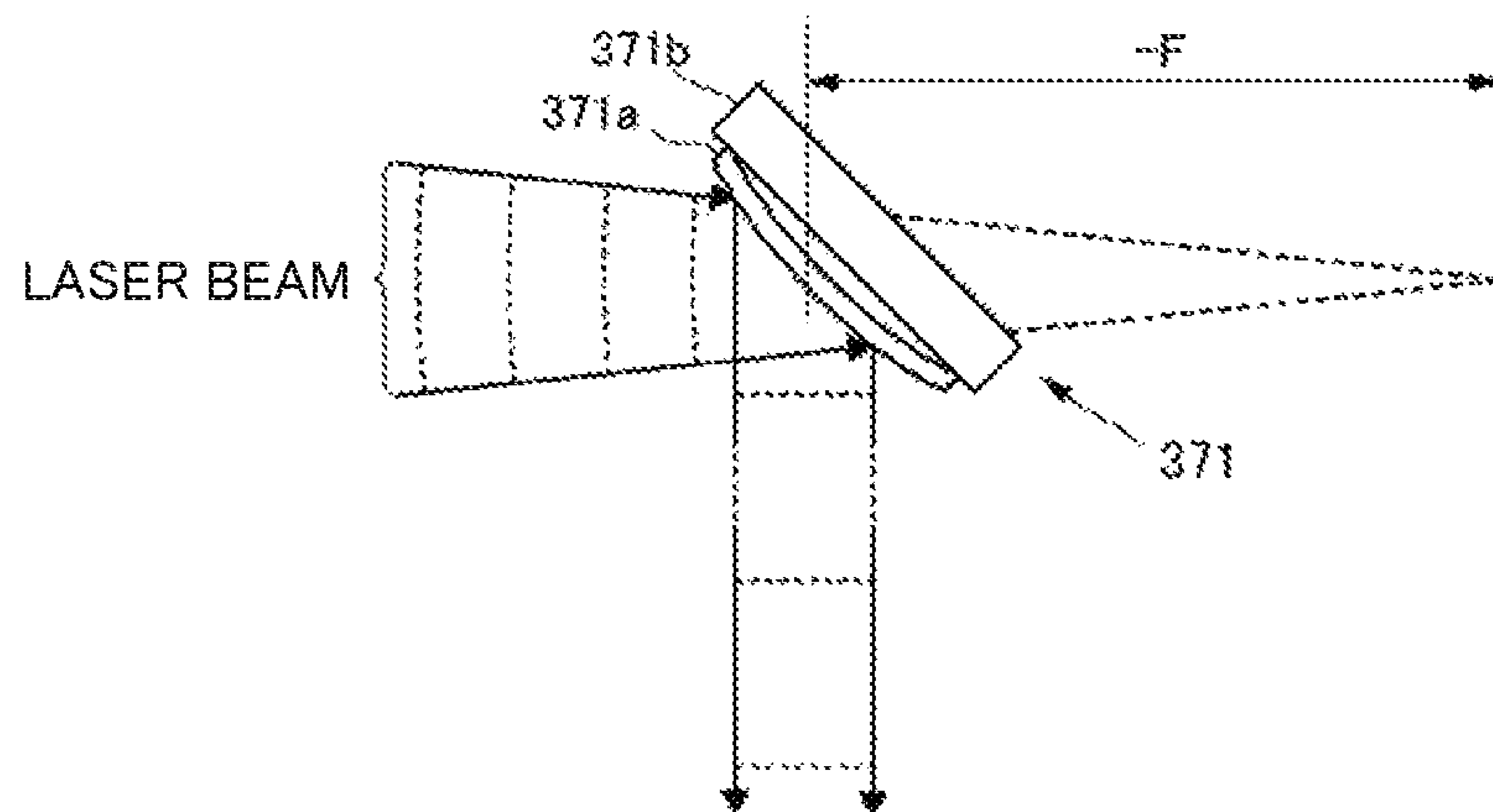


FIG. 11 C



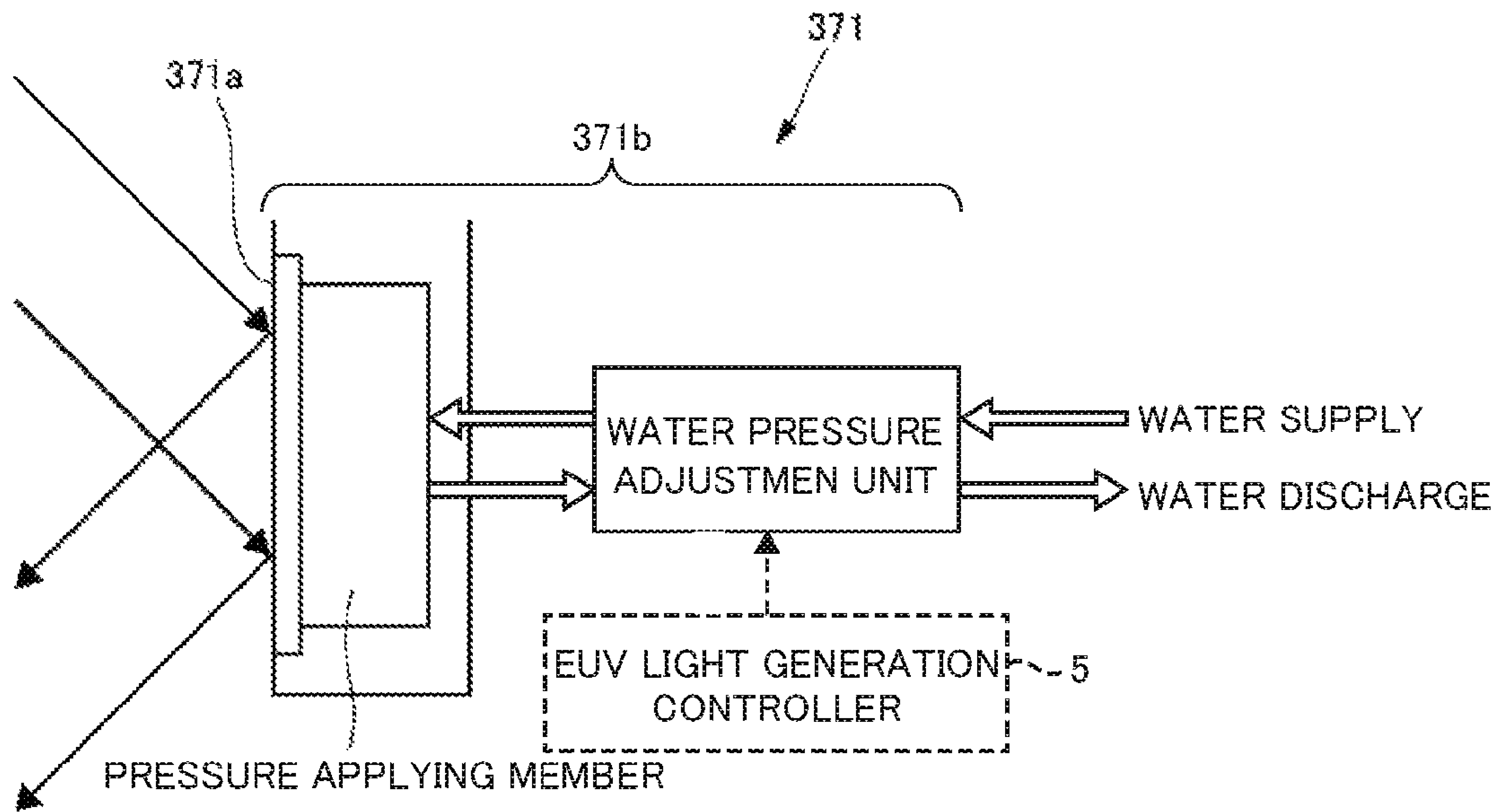


FIG.12

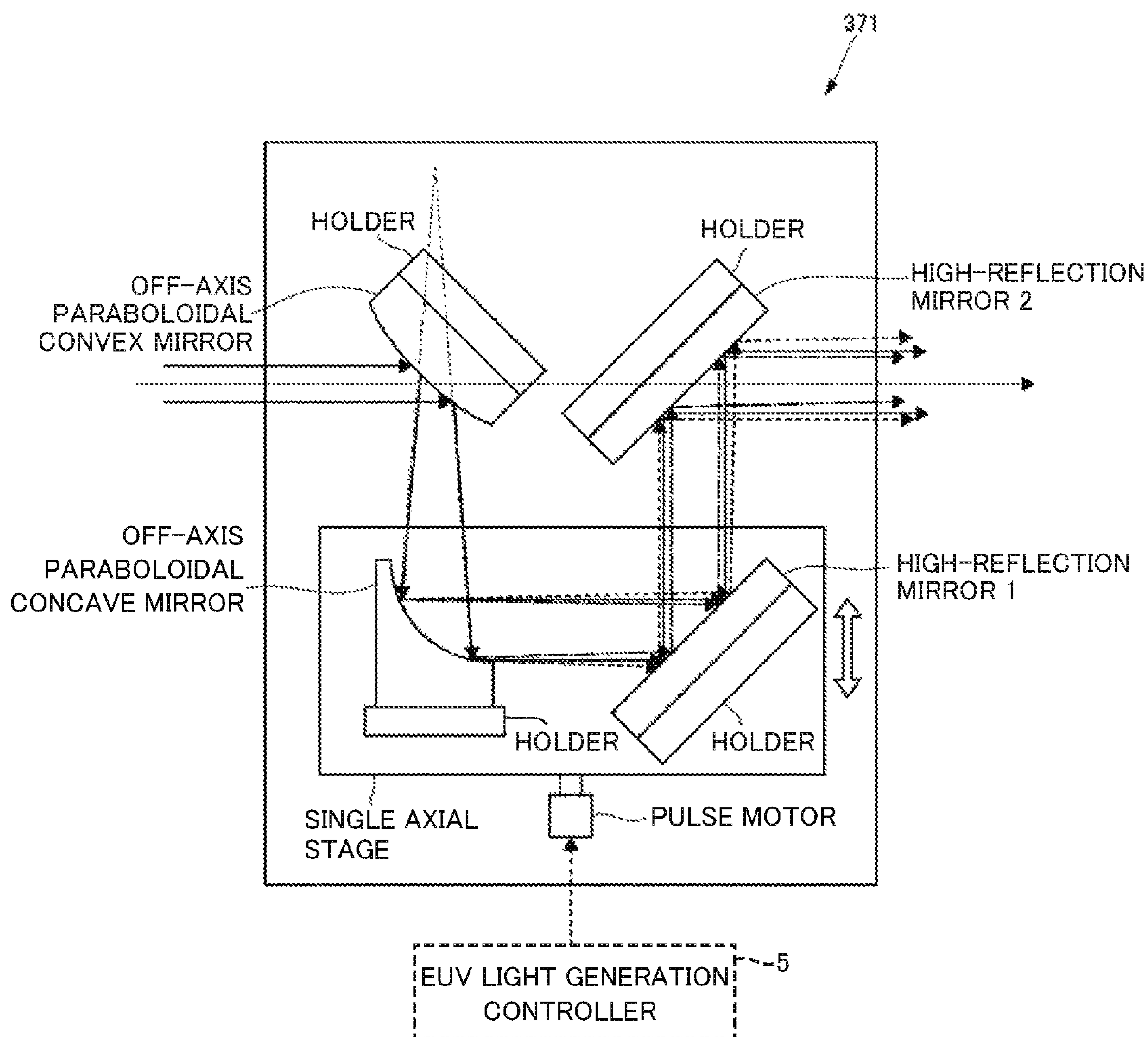


FIG. 13

MIRROR DEVICE

CROSS-REFERENCES TO RELATED APPLICATIONS

This application claims the benefit of International Patent Application No. PCT/JP2014/059436 filed Mar. 31, 2014, which is incorporated herein by reference.

BACKGROUND

1. Technical Field

The present disclosure relates to a mirror device.

In recent years, as semiconductor processes become finer, transfer patterns for use photolithographies of semiconductor processes have rapidly become finer. In the next generation, microfabrication at 70 nm to 45 nm, further, microfabrication at 32 nm or less would be demanded. In order to meet the demand for microfabrication at 32 nm or less, for example, it is expected to develop an exposure device in which a system for generating extreme ultraviolet (EUV) light at a wavelength of approximately 13 nm is combined with a reduced projection reflective optical system.

Three types of EUV light generation systems have been proposed, which include an LPP (laser produced plasma) type system using plasma generated by irradiating a target material with a laser beam, a DPP (discharge produced plasma) type system using plasma generated by electric discharge, and an SR (synchrotron radiation) type system using synchrotron orbital radiation.

CITATION LIST

Patent Literature

PTL1: Japanese Patent Application Laid-Open No. 2012-69907

PTL2: Japanese Patent Application Laid-Open No. 2013-115176

SUMMARY

According to an aspect of the present disclosure, a mirror device may include: an optical element configured to reflect part of a laser beam and transmit the other part of the laser beam therethrough; and a holder in surface contact with the optical element to hold the optical element. A flatness of a contact surface of the holder in contact with the optical element may be equal to or smaller than a flatness of the optical element.

According to an aspect of the present disclosure, a mirror device may include: an optical element configured to reflect part of a laser beam and transmit the other part of the laser beam therethrough; and a holder in surface contact with the optical element to hold the optical element. When a wavelength of the laser beam reflected from a surface of the optical element is λ, a flatness of a contact surface of the holder in contact with the optical element may be equal to or smaller than one-fifth of λ.

BRIEF DESCRIPTION OF THE DRAWINGS

Hereinafter, selected embodiments of the present disclosure will be described with reference to the accompanying drawings by way of example.

FIG. **1** schematically shows the configuration of an exemplary LPP type EUV light generation system;

FIG. **2** is a drawing explaining the configuration of a laser device including a laser oscillator and amplifiers;

FIG. **3** is a drawing explaining the configuration of a beam property measurement unit of a wavefront control system;

FIG. **4**A is a drawing explaining a first example of the mirror device;

FIG. **4**B is a cross-sectional view showing the mirror device taken along line IVB-IVB shown in FIG. **4**A;

FIG. **4**C is a cross-sectional view showing the mirror device taken along line IVC-IVC shown in FIG. **4**B;

FIG. **4**D is a drawing explaining the flatness of each of a support member and an optical element shown in FIG. **4**B;

FIG. **5**A is a drawing explaining a second example of the mirror device;

FIG. **5**B is a drawing explaining the flatness of each of the support member, a first intermediate member, and the optical element shown in FIG. **5**A;

FIG. **6**A is a drawing explaining a third example of the mirror device;

FIG. **6**B is a drawing explaining the flatness of each of the support member, a second intermediate member, and the optical element shown in FIG. **6**A;

FIG. **7** is a drawing explaining a modification of the third example of the mirror device;

FIG. **8** is a drawing explaining a fourth example of the mirror device;

FIG. **9** is a drawing explaining an EUV light generation apparatus including the mirror device;

FIG. **10** is a block diagram showing a hardware environment of each of the controllers;

FIG. **11**A is a drawing explaining the configuration of a wavefront adjustment unit, where a laser beam entering the wavefront adjustment unit is a plane wave;

FIG. **11**B is a drawing explaining the configuration of the wavefront adjustment unit, where a laser beam entering the wavefront adjustment unit is a convex wave;

FIG. **11**C is a drawing explaining the configuration of the wavefront adjustment unit, where a laser beam entering the wavefront adjustment unit is a concave wave;

FIG. **12** is a drawing explaining an actuator of the wavefront adjustment unit shown in FIGS. **11**A to **11**C; and

FIG. **13** is a drawing explaining another example of the configuration of the wavefront adjustment unit.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

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2. Description of terms
3. Overview of the EUV light generation system
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3.2 Operation
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4.2 Operation
4.3 Problem
5. Mirror device according to the present embodiment
5.1 First example of the mirror device
5.2 Second example of the mirror device
5.3 Third example of the mirror device
5.4 Fourth example of the mirror device
6. EUV light generation apparatus including the mirror device

6.1 Configuration
6.2 Operation
6.3 Effect
7. Others
7.1 Hardware environment of each controller
7.2 Wavefront adjustment unit
7.3 Modification

Hereinafter, selected embodiments of the present disclosure will be described in detail with reference to the accompanying drawings. The embodiments to be described below are merely illustrative in nature and do not limit the scope of the present disclosure. Further, the configuration(s) and operation(s) described in each embodiment are not all essential in implementing the present disclosure. Corresponding elements may be referenced by corresponding reference numerals and characters, and therefore duplicate descriptions will be omitted.

1. Overview

The present disclosure may at least disclose the following embodiments.

A mirror device **35** may include an optical element **350** configured to reflect part of an entering laser beam and to transmit the other part of the laser beam therethrough, and a holder **351** in surface contact with the optical element **350** to hold the optical element **350**. The flatness of a contact surface **352*f*** of the holder **351** in contact with the optical element **350** may be equal to or smaller than the flatness of the optical element **350**. With this configuration, the mirror device **35** can prevent the mismatch between the wavefront of the reflected light and the wavefront of the transmitted light.

2. Description of Terms

"Target" refers to a substance which is introduced into a chamber and is irradiated with a laser beam. The target irradiated with the laser beam is turned into plasma and emits EUV light. "Droplet" refers to one form of the target supplied into the chamber. "Axis of an optical path" refers to an axis passing through the center of the beam cross-section of a pulsed laser beam along the traveling direction of the pulsed laser beam. "Optical path" refers to a path through which the pulsed laser beam passes. The optical path may include the axis of the optical path. "Upstream side" of the optical path of the pulsed laser beam is the side near the laser oscillator. Meanwhile, "downstream side" of the optical path of the pulsed laser beam is the side far from the laser oscillator. "Flatness" means the magnitude of the difference from the geometrically correct plane (geometric plane) of a planar object (Japanese Industrial Standards JIS B 0621:1984). The flatness is defined by the minimum distance between two geometrically parallel planes when the planar object is sandwiched between the two planes (Japanese Industrial Standards JIS B 0621:1984). When the flatness is smaller, the planar object approximates to the geometric planer surface. That is, the smaller the flatness is, the better it is. The flatness can be one index of the surface accuracy.

3. Overview of the EUV Light Generation System

3.1 Configuration

FIG. **1** schematically shows the configuration of an exemplary LPP type EUV light generation system. An EUV light generation apparatus **1** may be used with at least one laser device **3**. In the present disclosure, the system including the EUV light generation apparatus **1** and the laser device **3** may be referred to as an EUV light generation system **11**. As shown in FIG. **1**, and as described in detail later, the EUV light generation apparatus **1** may include a chamber **2** and a target supply part **26**. The chamber **2** may be sealed airtight. The target supply part **26** may be mounted onto the chamber **2**, for example, to penetrate a wall of the chamber **2**. A target material to be supplied from the target supply part **26** may include, but is not limited to, tin, terbium, gadolinium, lithium, xenon, or a combination of any two or more of them.

The chamber **2** may have at least one through-hole in its wall. A window **21** may be provided on the through-hole. A pulsed laser beam **32** outputted from the laser device **3** may transmit through the window **21**. In the chamber **2**, an EUV collector mirror **23** having a spheroidal reflective surface may be provided. The EUV collector mirror **23** may have a first focusing point and a second focusing point. The surface of the EUV collector mirror **23** may have a multi-layered reflective film in which molybdenum layers and silicon layers are alternately laminated. The EUV collector mirror **23** may be arranged such that the first focusing point is positioned in a plasma generation region **25** and the second focusing point is positioned in an intermediate focusing (IF) point **292**. The EUV collector mirror **23** may have a through-hole **24** formed at the center thereof so that a pulsed laser beam **33** may pass through the through-hole **24**.

The EUV light generation apparatus **1** may further include an EUV light generation controller **5** and a target sensor **4**. The target sensor **4** may have an imaging function and detect the presence, trajectory, position, speed, and so forth of the target **27**.

Further, the EUV light generation apparatus **1** may include a connection part **29** that allows the interior of the chamber **2** to be in communication with the interior of an exposure device **6**. In the connection part **29**, a wall **291** having an aperture **293** may be provided. The wall **291** may be positioned such that the second focusing point of the EUV collector mirror **23** lies in the aperture **293**.

The EUV light generation apparatus **1** may also include a laser beam direction control unit **34**, a laser beam focusing mirror **22**, and the target collector **28** for collecting the target **27**. The laser beam direction control unit **34** may include an optical element for defining the traveling direction of the laser beam and an actuator for adjusting the position, the posture and so forth of the optical element.

3.2 Operation

With reference to FIG. **1**, a pulsed laser beam **31** outputted from the laser device **3** may pass through the laser beam direction control unit **34**, transmit through the window **21** as a pulsed laser beam **32**, and then enter the chamber **2**. The pulsed laser beam **32** may travel through the chamber **2** along at least one laser beam path, be reflected from the laser beam focusing mirror **22**, and be applied to at least one target **27** as the pulsed laser beam **33**.

The target supply part **26** may be configured to output the target **27** to the plasma generation region **25** in the chamber **2**. The target **27** may be irradiated with at least one pulse of the pulsed laser beam **33**. Upon being irradiated with the pulsed laser beam, the target **27** may be turned into plasma, and EUV light **251** may be emitted from the plasma together with the emission of light at different wavelengths. The EUV light **251** may be selectively reflected from the EUV collector mirror **23**. EUV light **252** reflected from the EUV collector mirror **23** may be focused onto the IF point **292**, and outputted to the exposure device **6**. Here, one target **27** may be irradiated with multiple pulses of the pulsed laser beam **33**.

The EUV light generation controller **5** may be configured to totally control the EUV light generation system **11**. The EUV light generation controller **5** may be configured to process the image data of the target **27** captured by the target

sensor **4**. Further, the EUV light generation controller **5** may be configured to control at least one of: the timing at which the target **27** is outputted; and the direction in which the target **27** is outputted. Furthermore, the EUV light generation controller **5** may be configured to control at least one of: the timing at which the laser device **3** oscillates; the traveling direction of the pulsed laser beam **32**; and the position on which the pulsed laser beam **33** is focused. The various controls described above are merely examples, and other controls may be added as necessary.

4. Laser Device Including a Laser Oscillator and Amplifiers

4.1 Configuration

Now, with reference to FIGS. **2** and **3**, the laser device **3** including a laser oscillator **301** and an amplifier **310** will be described. FIG. **2** is a drawing explaining the configuration of the laser device **3** including the laser oscillator **301** and the amplifier **310**.

The laser device **3** of the EUV light generation system **11** may include the laser oscillator **301**, the amplifier **310**, a wavefront control system **320**, and a laser controller **330**. The laser oscillator **301** and the amplifier **310** may constitute an MOPA (master oscillator power amplifier) system. Here, the amplifier **310** may be constituted by one or more amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$. The one or more amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$ may be collectively referred to as "amplifier **310**."

The laser oscillator **301** may be a master oscillator which constitutes the MOPA system. The laser oscillator **301** may be a gas laser. The laser oscillator **301** may be a gas laser that includes a pair of discharge electrodes, an optical resonator and a Q switch, and that uses CO_2 as laser gas. Alternatively, the laser oscillator **301** may be a semiconductor laser. The laser oscillator **301** may be a quantum-cascade laser that oscillates at a wavelength of the gain region of the CO_2 gas laser. The laser oscillator **301** may oscillate and emit a pulsed laser beam **30** to the subsequent amplifier **310**. The pulsed laser beam **30** may include a seed beam, which is a laser beam having not been amplified by the amplifier **310**. The wavelength of the pulsed laser beam **30** may be, for example, about 9 μm to 10.6 μm.

The amplifier **310** may be a power amplifier constituting the MOPA system. The amplifier **310** may be a gas laser. The amplifier **310** may be a gas laser that includes a pair of discharge electrodes and uses CO_2 as laser gas. A discharge voltage may be applied to the pair of discharge electrodes of the amplifier **310**, from a high-frequency power source (not shown). The amplifier **310** may be a triaxial orthogonal amplifier, or a fast-axial-flow amplifier. Otherwise, the amplifier **310** may be a slab amplifier. The amplifier **310** may be disposed on the optical path of the pulsed laser beam **30** emitted from the laser oscillator **301**.

As described above, the amplifier **310** may be constituted by one or more amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$. The amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$ may be arranged in series on the optical path of the pulsed laser beam **30** emitted from the laser oscillator **301**. The amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$ may receive the pulsed laser beams emitted from the preceding laser oscillator **301** or amplifiers $\mathbf{310}_1$ to $\mathbf{310}_{n-1}$, respectively. The amplifiers $\mathbf{310}_1$ to $\mathbf{310}_{n-1}$ may amplify the received pulsed laser beams, and emit the amplified beams to the respective subsequent amplifiers $\mathbf{310}_2$ to $\mathbf{310}_n$. The last amplifier $\mathbf{310}_n$ may amplify the received pulsed laser beam, and emit the amplified pulsed laser beam to the laser beam direction control unit **34** as the pulsed laser beam **31**.

The wavefront control system **320** may be configured to control the wavefront of the pulsed laser beam **30** emitted from the amplifier **310**. The wavefront control system **320** may include a beam property measurement unit **321**, a wavefront adjustment unit **322**, and a controller **323**. Here, the wavefront control system **320** may be constituted by one or more wavefront control systems $\mathbf{320}_1$ to $\mathbf{320}_m$. The one or more wavefront control systems $\mathbf{320}_1$ to $\mathbf{320}_m$ may be collectively referred to as "wavefront control system **320**." In addition, the wavefront control systems $\mathbf{320}_1$ to $\mathbf{320}_m$ may include the beam property measurement units $\mathbf{321}_1$ to $\mathbf{321}_m$, the wavefront adjustment units $\mathbf{322}_1$ to $\mathbf{322}_m$ and the controllers $\mathbf{323}_1$ to $\mathbf{323}_m$, respectively. The beam property measurement units $\mathbf{321}_1$ to $\mathbf{321}_m$ may be collectively referred to as "beam property measurement unit **321**." The wavefront adjustment units $\mathbf{322}_1$ to $\mathbf{322}_m$ may be collectively referred to as "wavefront adjustment unit **322**." The controllers $\mathbf{323}_1$ to $\mathbf{323}_m$ may be collectively referred to as "controller **323**."

The beam property measurement unit **321** may be provided on the downstream side with respect to the amplifier **310**, on the optical path of the pulsed laser beam **30** emitted from the laser oscillator **301**. The beam property measurement unit **321** may measure various beam properties of the pulsed laser beam **30** emitted from the amplifier **310**. The beam properties measured by the beam property measurement unit **321** may include beam divergence. The beam divergence may indicate the spread angle of a laser beam, which may be a parameter for the wavefront of the pulsed laser beam **30**. The radius of curvature of the wavefront may be calculated from the beam divergence. The beam property measurement unit **321** may generate a measurement signal related to the measured beam property, and output the signal to the controller **323**. The detailed configuration of the beam property measurement unit **321** will be described later with reference to FIG. **3**.

The wavefront adjustment unit **322** may be provided on the upstream side with respect to the amplifier **310**, on the optical path of the pulsed laser beam **30** emitted from the laser oscillator **301**. The wavefront adjustment unit **322** may adjust the wavefront of the pulsed laser beam entering the amplifier **310**. The wavefront adjustment unit **322** may include a concave lens, a convex lens, and a movable stage (not shown). The concave lens and the convex lens of the wavefront adjustment unit **322** may be placed on the movable stage to face one another. The concave lens and the convex lens placed on the movable stage may be located on the optical path of the pulsed laser beam **30**. The movable stage may change the distance between the concave lens and the convex lens. The wavefront adjustment unit **322** may drive the movable stage to change the distance between the concave lens and the convex lens, according to a control signal from the controller **323**.

The controller **323** may control the operations of the beam property measurement unit **321** and the wavefront adjustment unit **322** of the wavefront control system **320**, based on a command from the laser controller **330**. The controller **323** may receive, from the beam property measurement unit **321**, the measurement signal related to the beam property of the pulsed laser beam **30** emitted from the amplifier **310**. The controller **323** may output a control signal to control the wavefront of the pulsed laser beam **30** entering the amplifier **310**, to the wavefront adjustment unit **322**, based on the inputted measurement signal. The control signal may be a signal for changing the distance between the concave lens and the convex lens of the wavefront adjustment unit **322** to make the wavefront of the pulsed laser beam **30** entering the amplifier **310** have a desired radius of curvature. By this means, the wavefront of the pulsed laser beam **30** entering the amplifier **310** may be adjusted to a wavefront with a desired radius of curvature, according to the control of the

controller **323**. Here, a hardware configuration of the controller **323** will be described later with reference to FIG. **10**.

As described above, the wavefront control system **320** may be constituted by one or more wavefront control systems $\mathbf{320}_1$ to $\mathbf{320}_m$. The wavefront control systems $\mathbf{320}_1$ to $\mathbf{320}_m$ may be provided to correspond to the amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$, respectively in one-to-one correspondence. Alternatively, the wavefront control systems $\mathbf{320}_1$ to $\mathbf{320}_m$ may be provided to correspond to part of the amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$, respectively. A specified amplifier **310** of the amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$ may be referred to as "amplifier $\mathbf{310}_k$." A specified wavefront control system **320** of the wavefront control systems $\mathbf{320}_1$ to $\mathbf{320}_m$, which is provided for the amplifier $\mathbf{310}_k$, may be referred to as "wavefront control system $\mathbf{320}_k$." The beam property measurement unit **321**, the wavefront adjustment unit **322**, and the controller **323** which are included in the waveform control system $\mathbf{320}_k$ may be referred to as "beam property measurement unit $\mathbf{321}_k$", "wavefront adjustment unit $\mathbf{322}_k$", and "controller $\mathbf{323}_k$", respectively. That is, the wavefront adjustment unit $\mathbf{322}_k$ may be provided on the upstream side with respect to the amplifier $\mathbf{310}_k$ while the beam property measurement unit $\mathbf{321}_k$ may be provided on the downstream side with respect to the amplifier $\mathbf{310}_k$. The wavefront adjustment unit $\mathbf{322}_k$ and the beam property measurement unit $\mathbf{321}_k$ may be connected to the controller $\mathbf{323}_k$.

The laser controller **330** may be connected to the EUV light generation controller **5** and send/receive various signals to/from the EUV light generation controller **5**. For example, the laser controller **330** may receive a command signal related to the oscillation of the pulsed laser beam **30** from the EUV light generation controller **5**. The command signal from the EUV light generation controller **5** may contain information for controlling the oscillation timing, the repetition frequency, the beam divergence, the optical path, the pulse energy and so forth of the pulsed laser beam **30**. The laser controller **330** may totally control the operation of each of the components of the laser device **3**, based on the command signal from the EUV light generation controller **5**. The laser controller **330** may control the laser oscillation of the laser oscillator **301** and the laser amplification of the amplifier **310**. The laser controller **330** may cause the controller **323** to control the wavefront control system **320**. Here, the hardware configuration of the laser controller **330** will be described later with reference to FIG. **10**.

FIG. **3** is a drawing explaining the configuration of the beam property measurement unit $\mathbf{321}_k$ of the wavefront control system $\mathbf{320}_k$. The beam property measurement unit $\mathbf{321}_k$ may include a beam splitter $\mathbf{321}a_k$, a light focusing optical system $\mathbf{321}b_k$, a two-dimensional image sensor $\mathbf{321}c_k$, and a holder $\mathbf{321}d_k$.

The beam splitter $\mathbf{321}a_k$ may reflect part of the entering pulsed laser beam **30** and transmit the other part of the pulsed laser beam **30** therethrough. The beam splitter $\mathbf{321}a_k$ may be disposed at a predetermined position on the optical path of the pulsed laser beam **30** emitted from the laser oscillator **301**. The beam splitter $\mathbf{321}a_k$ may be disposed in a posture that allows the pulsed laser beam **30** having transmitted through the beam splitter $\mathbf{321}a_k$ to travel on the optical path of the pulsed laser beam **30** emitted from the laser oscillator **301**. At this time, the beam splitter $\mathbf{321}a_k$ may be disposed in the posture that allows the pulsed laser beam **30** reflected from the beam splitter $\mathbf{321}a_k$ to enter the light focusing optical system $\mathbf{321}b_k$. The beam splitter $\mathbf{321}a_k$ may divide the entering pulsed laser beam **30** into the pulsed laser beam **30** to be emitted to the subsequent wavefront control system $\mathbf{320}_k$++ and the pulsed laser beam **30** to be emitted to the light focusing optical system $\mathbf{321}b_k$.

The light focusing optical system $\mathbf{321}b_k$ may focus the pulsed laser beam **30** reflected from the beam splitter $\mathbf{321}a_k$ onto a light receiving surface of the two-dimensional image sensor $\mathbf{321}c_k$.

The two-dimensional image sensor $\mathbf{321}c_k$ may measure the various beam properties of the pulsed laser beam **30** focused by the light focusing optical system $\mathbf{321}b_k$. The beam properties may include the beam divergence. The two-dimensional image sensor $\mathbf{321}c_k$ may generate a measurement signal related to the measured beam properties, and output the signal to the controller **323**.

The holder $\mathbf{321}d_k$ may hold the beam splitter $\mathbf{321}a_k$ to place the beam splitter $\mathbf{321}a_k$ in the predetermined posture at the predetermined position. A flow channel through which a refrigerant flows may be provided inside the holder $\mathbf{321}d_k$. The refrigerant may be cooling water. The holder $\mathbf{321}d_k$ may cool the beam splitter $\mathbf{321}a_k$ generating heat due to the absorption of the pulsed laser beam **30**.

4.2 Operation

The laser controller **330** may control the high-frequency power source to apply a discharge voltage to the discharge electrodes of the amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$. Before the pulsed laser beam **30** from the laser oscillator **301** enters the amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$, discharges may be started in the amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$. The laser gas in the amplifiers $\mathbf{310}_1$ to $\mathbf{310}_n$ may be excited in advance.

The laser controller **330** may control the oscillation of the laser oscillator **301** to emit the pulsed laser beam **30** at a predetermined repetition frequency. The pulsed laser beam **30** emitted from the laser oscillator **301** may enter the first amplifier $\mathbf{310}_1$ and be amplified by the amplifier $\mathbf{310}_1$. The pulsed laser beam **30** amplified by the amplifier $\mathbf{310}_1$ may enter the subsequent amplifier $\mathbf{310}_2$ and be further amplified by the amplifier $\mathbf{310}_2$. Subsequently, the amplification may be performed in the amplifiers $\mathbf{310}_3$ to $\mathbf{310}_n$ in the same way as the amplifier $\mathbf{310}_1$ and the amplifier $\mathbf{310}_2$. The pulsed laser beam **30** amplified by the last amplifier $\mathbf{310}_n$ may be emitted to the laser beam direction control unit **34**, as the pulsed laser beam **31**.

Here, when the wavefront control system is provided in the amplifier **310**, the pulsed laser beam **30** may be amplified as follows. The pulsed laser beam **30** emitted from the amplifier $\mathbf{310}_{k-1}$ provided on the upstream side with respect to the amplifier $\mathbf{310}_k$ may enter the wavefront adjustment unit $\mathbf{322}_k$ of the wavefront control system $\mathbf{320}_k$. The wavefront adjustment unit $\mathbf{322}_k$ may adjust the wavefront of the entering pulsed laser beam **30** and emit the adjusted pulsed laser beam **30** to the amplifier $\mathbf{310}_k$. The amplifier $\mathbf{310}_k$ may amplify the pulsed laser beam **30** whose wavefront has been adjusted by the wavefront adjustment unit $\mathbf{322}_k$.

Part of the pulsed laser beam **30** amplified by the amplifier $\mathbf{310}_k$ may transmit through the beam splitter $\mathbf{321}a_k$ of the beam property measurement unit $\mathbf{321}_k$, and enter the amplifier $\mathbf{310}_{k+1}$ or the wavefront adjustment unit $\mathbf{322}_{k+1}$. The other part of the pulsed laser beam **30** amplified by the amplifier $\mathbf{310}_k$ may be reflected from the beam splitter $\mathbf{321}a_k$ of the beam property measurement unit $\mathbf{321}_k$ and focused onto the two-dimensional image sensor $\mathbf{321}c_k$. The two-dimensional image sensor $\mathbf{321}c_k$ may measure the beam properties of the entering pulsed laser beam **30**, and output a measurement signal related to the measured beam properties to the controller $\mathbf{323}_k$. The controller $\mathbf{323}_k$ may control the wavefront adjustment unit $\mathbf{322}_k$ by feedback control to achieve desired beam properties, based on the inputted measurement signal.

4.3 Problem

As described above, the high-power pulsed laser beam **30** amplified by the amplifier $\mathbf{310}_k$ may enter the beam splitter $\mathbf{321}a_k$ of the beam property measurement unit $\mathbf{321}_k$. Upon receiving the high-power pulsed laser beam **30**, the beam splitter $\mathbf{321}a_k$ may absorb part of the pulsed laser beam **30**, and therefore generate heat. The beam splitter $\mathbf{321}a_k$ generating heat may thermally expand. The beam splitter $\mathbf{321}a_k$ may be tightened and cooled by the holder $\mathbf{321}d_k$ through which the refrigerant flows. In this case, the thermal expansion and shrinkage of the beam splitter $\mathbf{321}a_k$ may be restricted because the beam splitter $\mathbf{321}a_k$ is tightened by the holder $\mathbf{321}d_k$. Then, in the beam splitter $\mathbf{321}a_k$, a thermal stress corresponding to the difference in the coefficient of thermal expansion between the beam splitter $\mathbf{321}a_k$ and the holder $\mathbf{321}d_k$ may be generated. By this means, the beam splitter $\mathbf{321}a_k$ may not shrink as it was before the expansion, and then may be distorted. If the beam splitter $\mathbf{321}a_k$ is distorted, the beam properties of the pulsed laser beam **30** reflected from the beam splitter $\mathbf{321}a_k$ may be changed. In particular, the wavefront of the pulsed laser beam **30** may be easy to be changed from the wavefront obtained from the beam splitter $\mathbf{321}a_k$ having not been distorted. Then, the wavefront of the pulsed laser beam **30** reflected from the beam splitter $\mathbf{321}a_k$ may not match the wavefront of the pulsed laser beam **30** having transmitted through the beam splitter $\mathbf{321}a_k$. Therefore, there has been a problem that it is not possible to achieve the desired beam properties of the pulsed laser beam **30** emitted from the amplifier $\mathbf{310}_k$, even though the wavefront adjustment unit $\mathbf{322}_k$ is controlled by feedback control based on the beam properties measured by the beam property measurement unit $\mathbf{321}_k$. This problem may not be limited to the beam property measurement unit $\mathbf{321}_k$ including the beam splitter $\mathbf{321}a_k$ and the holder $\mathbf{321}d_k$, but apply equally to a mirror device that includes an optical element configured to reflect part of a laser beam and to transmit the other of the laser beam therethrough, and a holder configured to hold the optical element. Therefore, there is a demand for a technology that can prevent the distortion of the optical element generating heat while being held by the holder.

5. Mirror Device According to the Present Embodiment

Now, with reference to FIGS. **4**A to **8**, the mirror device **35** according to the present embodiment will be described. In the mirror device **35** according to the present embodiment, the configurations of the optical element and the holder may be different from the configurations of the beam splitter $\mathbf{321}a_k$ and the holder $\mathbf{321}d_k$ shown in FIG. **3**. In the mirror device **35** according to the present embodiment, the configurations which are the same as the configurations of the beam splitter $\mathbf{321}a_k$ and the holder $\mathbf{321}d_k$ shown in FIG. **3** will not be described again here. Examples of the mirror device **35** will be described as first to fourth examples.

5.1 First Example of the Mirror Device

Now, with reference to FIGS. **4**A to **4**D, the first example of the mirror device **35** will be described. FIG. **4**A is a drawing explaining the first example of the mirror device **35**. FIG. **4**B is a cross-sectional view showing the mirror device **35** taken along line IVB-IVB shown in FIG. **4**A. FIG. **4**C is a cross-sectional view showing the mirror device **35** taken along line IVC-IVC shown in FIG. **4**B.

The first example of the mirror device **35** may include the optical element **350** and the holder **351**.

The optical element **350** may be configured to reflect part of the entering pulsed laser beam **30** and transmit the other part of the pulsed laser beam **30** therethrough. The optical element **350** may be, for example, a beam splitter or a dichroic mirror. The optical element **350** may be formed as a circular plate. The optical element **350** may have a planer structure. The optical element **350** may be formed by using a diamond substrate. When the power of the pulsed laser beam **30** is low, the optical element **350** may be formed by using a GaAs substrate. However, when the power of the pulsed laser beam **30** is equal to or higher than several kW, the optical element **350** may be preferably formed by using a diamond substrate.

The optical element **350** may include at least a first surface **350***a* and a second surface **350***b*. The first surface **350***a* may be an entrance plane of the optical element **350** into which the pulsed laser beam **30** enters. A reflection coating to reflect part of the pulsed laser beam **30** may be applied to the first surface **350***a*. The second surface **350***b* may be the opposite surface of the first surface **350***a*. The second surface **350***b* may be an exit plane of the optical element **350** from which part of the pulsed laser beam **30** having transmitted through the optical element **350** exits. An antireflective coating to prevent the reflection of the pulsed laser beam **30** may be applied to the second surface **350***b*. Part of the pulsed laser beam **30** entering the optical element **350** may be reflected from the first surface **350***a* as reflected beam. The other part of the pulsed laser beam **30** entering the optical element **350** may transmit through the first surface **350***a* and the interior of the optical element **350**, and exit the second surface **350***b* as transmitted beam.

The holder **351** may accommodate the optical element **350** and hold the optical element **350** therein. The holder **351** may be in surface contact with the optical element **350** to hold the optical element **350**. The holder **351** may be formed into a hollow cylindrical shape. The holder **351** may include a support member **352**, pushing members **353**, a fixing member **354**, screws **355**, and joints **356**. The support member **352** and the fixing member **354** may constitute the frame of the holder **351**.

The support member **352** may be in surface contact with the optical element **350** to support the optical element **350**. The support member **352** may be formed by using a metallic material or a ceramic material. The metallic material for forming the support member **352** may be stainless steel or copper, or contain copper. The ceramic material for forming the support member **352** may be SiC (silicon carbide). The support member **352** may include a through-hole **352***a*, a flow channel **352***b*, a refrigerant inlet **352***c*, a refrigerant outlet **352***d*, a front surface **352***e*, a contact surface **352***f*, and tapped holes **352***g*.

The support member **352** may be formed as a circular plate. The outside diameter of the support member **352** may be greater than the diameter of the optical element **350**. The central axis of the support member **352** may match the central axis of the optical element **350** set in the support member **352**. The through-hole **352***a* may be formed in the center of the support member **352**. The through-hole **352***a* may be configured to guide the pulsed laser beam **30** entering the mirror device **35** to the optical element **350**. The diameter of the through-hole **352***a* may be greater than the diameter of the pulsed laser beam **30** and smaller than the diameter of the optical element **350**. The central axis of the through-hole **352***a* may match the central axis of the optical element **350** set in the support member **352**.

The flow channel **352***b* through which a refrigerant flows may be formed inside of the support member **352** which is located radially outside of the through-hole **352***a*. The refrigerant may be cooling water. The position of the flow channel **352***b* in the support member **352** may correspond to the position of an outer edge **350***c* of the optical element **350**

set in the support member **352**. Here, the outer edge **350***c* of the optical element **350** set in the support member **352** may be located radially outside of the through-hole **352***a*.

The flow channel **352***b* may be provided with the refrigerant inlet **352***c* and the refrigerant outlet **352***d*. The refrigerant inlet **352***c* may be an inlet to flow the refrigerant into the flow channel **352***b*. The refrigerant outlet **352***d* may be an outlet to flow the refrigerant out of the flow channel **352***b*. The joints **356** may be mounted to the refrigerant inlet **352***c* and the refrigerant outlet **352***d*. The refrigerant inlet **352***c* and the refrigerant outlet **352***d* may be jointed to pipes (not shown) via the joints **356**. The pipes may be connected to a pump (not shown). The flow channel **352***b*, the refrigerant inlet **352***c*, the refrigerant outlet **352***d*, the joints **356**, the pipes, and the pump may communicate with each other. The refrigerant flowing through the flow channel **352***b* may circulate in the flow channel **352***b* by driving the pump.

The heat generated in the optical element **350** due to the absorption of the pulsed laser beam **30** may be transferred to the support member **352** in surface contact with the optical element **350** by heat conduction. The heat transferred to the support member **352** may be transferred to the refrigerant circulating in the flow channel **352***b*, and then discharged to the outside of the mirror device **35**. By this means, the holder **351** may efficiently cool the optical element **350** generating heat due to the absorption of the pulsed laser beam **30** by the support member **352** in surface contact with the optical element **350** while the refrigerant flows through the support member **352**.

The front surface **352***e* of the support member **352** may be one side of the support member **352** into which the pulsed laser beam **30** enters. The contact surface **352***f* of the support member **352** may be the other side of the support member **352**, which is the opposite surface of the front surface **352***e*. The optical element **350** may be set on the contact surface **352***f*. The contact surface **352***f* may be in surface contact with the first surface **350***a* of the optical element **350**. The contact surface **352***f* may be in surface contact with the first surface **350***a* of the optical element **350** at the outer edge **350***c*. The contact surface **352***f* may be polished to provide a high surface accuracy. The surface accuracy may be tested by using a Fizeau interferometer. The parameter indicating the surface accuracy of the contact surface **352***f* may be flatness. The flatness of each of the contact surface **352***f* and the first surface **350***a* will be described later with reference to FIG. **4**D.

The tapped holes **352***g* may be formed in the contact surface **352***f* of the support member **352**. The tapped holes **352***g* may be female threads corresponding to the screws **355** which are male screws. The tapped holes **352***g* may be formed radially outside of the part of the contact surface **352***f* supporting the optical element **350**. The tapped holes **352***g* in the contact surface **352***f* may be located radially outside of the outer edge **350***c* of the optical element **350** set in the support member **352**.

The pushing members **353** may push the optical element **350** against the support member **352**. The pushing members **353** may push the second surface **350***b* of the optical element **350**. The pushing members **353** may include an elastic body such as a spring. The pushing members **353** may be plunger screws. The exterior part of the plunger screw may be threaded so as to be formed as a male screw. The front end of the plunger screw may be formed as a hemispherical pin or ball in contact with the optical element **350**. The elastic body such as a spring that applies a force to push out the pin or ball may be provided to be able to expand and shrink in the plunger screw.

The pushing members **353** may push the optical element **350** against the support member **352** by pushing the second surface **350***b*. At this time, the portions of the pushing members **353** in contact with the second surface **350***b* may slide on the second surface **350***b*. In addition, the portions of the pushing members **353** in contact with the second surface **350***b* may be expanded and shrunk by the elastic bodies of the pushing members **353** in the thickness direction of the optical element **350**. Therefore, the pushing members **353** may push the optical element **350** against the support member **352** without restricting the optical element **350** from thermally expanding and shrinking. By this means, even though the optical element **350** generating heat due to the absorption of the pulsed laser beam **30** is thermally expanded and shrunk by the cooling, the holder **351** may hold the optical element **350** without distorting the optical element **350**.

The pushing members **353** may push the second surface **350***b* of the optical element **350** at the outer edge **350***c*. The pushing members **353** may push the second surface **350***b* at at least three or more points of the outer edge **350***c*. The points of the second surface **350***b* pushed by the pushing members **353** may be symmetric with respect to the center of the optical element **350** set in the support member **352**. When there are three points pushed by the pushing members **353**, these points may be spaced from each other by 120 degrees along the circumferential direction of the through-hole **352***a*.

The pushing members **353** may push at least three or more points which are symmetric with respect to the center of the optical element **350**. By pushing the optical element **350** by those pushing members **353**, the force may be applied uniformly to the optical element **350**. Therefore, the stress generated in the optical element **350** by pushing the optical element **350** by the pushing members **353** may not be easy to be concentrated on the specified positions of the optical element **350** pushed by the pushing members **353**. By this means, even when the pushing members **353** push the optical element **350**, the holder **351** may hold the optical element **350** without distorting the optical element **350**. Here, leaf springs may be used as the pushing members **353**, instead of the plunger screws. The leaf springs as the pushing members **353** may be in surface contact with the optical element **350** to push the optical element **350**.

The fixing member **354** may fix the pushing members **353** pushing the optical element **350** against the support member **352**. The fixing member **354** may be formed by using a metallic material or a ceramic material. The material for forming the fixing member **354** may be the same as the material for forming the support member **352**. The fixing member **354** may include a side portion **354***a*, a bottom portion **354***b*, a through-hole **354***c*, tapped holes **354***d*, and insertion holes **354***e*.

The side portion **354***a* of the fixing member **354** may be formed into a hollow cylindrical shape. The inside diameter of the side portion **354***a* may be greater than the diameter of the optical element **350**. The outside diameter of the side portion **354***a* may be similar to the outside diameter of the support member **352**. The central axis of the side portion **354***a* may match the central axis of the optical element **350** set in the support member **352**. One end of the side portion **354***a* may be closed by the bottom portion **354***b*, but the other end of the side portion **354***a* may not be closed by the bottom portion **354***b*. The surface of the other end of the side portion **354***a* may be in surface contact with the contact surface **352***f* of the support member **352** when the fixing member **354** is coupled with the support member **352**.

The bottom portion **354***b* of the fixing member **354** may be a circular plate that closes the one end of the side portion **354***a* having a hollow cylindrical shape. The central axis of the bottom portion **354***b* may match the central axis of the optical element **350** set in the support member **352**. The through-hole **354***c* may be formed in the center of the bottom portion **354***b*. The through-hole **354***c* may be configured to guide the pulsed laser beam **30** having transmitted through the optical element **350** to the outside of the mirror device **35**. The diameter of the through-hole **354***c* may be greater than the diameter of the pulsed laser beam **30**, and smaller than the diameter of the optical element **350**. The central axis of the through-hole **354***c* may match the central axis of the optical element **350** set in the support member **352**.

The tapped holes **354***d* may be formed in the bottom portion **354***b* located radially outside of the through-hole **354***c*. The tapped holes **354***d* may be female threads corresponding to the pushing members **353** which are plunger screws as male screws. The tapped holes **354***d* may penetrate the bottom portion **354***b*. The positions of the tapped holes **354***d* in the bottom portion **354***b* may correspond to the positions of the pushing members **353** pushing the optical element **350** set in the support member **352**.

The insertion holes **354***e* may be formed in the bottom portion **354***b*. The insertion holes **354***e* may be configured to insert the screws **355** therein. The insertion holes **354***e* may penetrate the bottom portion **354***b*. The insertion holes **354***e* may penetrate the bottom portion **354***b* and the side portion **354***a*. The positions of the insertion holes **354***e* in the bottom portion **354***b* may correspond to the positions of the tapped holes **352***g* of the support member **352** when the fixing member **354** is coupled with the support member **352**. Here, the insertion holes **354***e* may be female threads corresponding to the screws **355**, like the tapped holes **352***g*.

The screws **355** may be members used to screw the fixing member **354** to the support member **352** after the fixing member **354** is coupled with the support member **352**. The screws **355** may be inserted into the insertion holes **354***e* of the fixing member **354** and fitted into the tapped holes **352***g* of the support member **352**.

With reference to FIG. **4**D, the flatness of each of the support member **352** and the optical element **350** will be described. FIG. **4**D is a drawing explaining the flatness of each of the support member **352** and the optical element **350** shown in FIG. **4**B.

The flatness of the optical element **350** may be, for example, equal to or smaller than at least one-fifth of a wavelength λ of the pulsed laser beam **30** reflected from the optical element **350**, as a PV (peak to valley) value. Preferably, the flatness of the optical element **350** may be equal to or smaller than one-tenth of the wavelength λ of the pulsed laser beam **30** reflected from the optical element **350**, as a PV value. The flatness of the contact surface of the holder **351** in contact with the optical element **350** may be equal to or smaller than the flatness of the optical element **350**. To be more specific, the flatness of the contact surface **352***f* of the support member **352** may be equal to or smaller than the flatness of the optical element **350**. Further more specifically, the flatness of the contact surface **352***f* of the support member **352** may be equal to or smaller than the flatness of the first surface **350***a* of the optical element **350**.

The flatness of the contact surface **352***f* of the support member **352** in surface contact with the optical element **350** may be equal to or better than the flatness of the optical element **350**. Therefore, the optical element **350** generating heat while being pushed against the support member **352** may thermally expand and shrink without being subjected to a locally applied force caused by the surface roughness and the irregularity of the contact surface **352***f*. Moreover, the contact thermal resistance between the optical element **350** and the support member **352** may be reduced, and therefore the heat generated in the optical element **350** may be easy to be transferred to the support member **352**. Accordingly, the temperature of the optical element **350** may not be easy to be increased, and therefore it is possible to reduce a change in the volume of the optical element **350** due to the thermal expansion. By this means, even though the optical element **350** generating heat due to the absorption of the pulsed laser beam **30** is thermally expanded and shrunk by the cooling, the holder **351** may hold the optical element **350** without distorting the optical element **350**.

With the above-described configuration according to the first example, the holder **351** can hold the optical element **350** by uniformly applying a force to the optical element **350**, without restricting the optical element **350** from thermally expanding and shrinking. In addition, according to the first example, the holder **351** can hold the optical element **350** thermally expanding and shrinking, without locally applying a force caused by the surface roughness and the irregularity of the contact surface **352***f* to the optical element **350**. Moreover, according to the first example, the holder **351** can reduce a change in the volume of the optical element **350** due to the thermal expansion. By this means, the first example of the mirror device **35** can prevent the optical element **350** from being distorted when the optical element **350** held by the holder **351** generates heat. Therefore, the first example of the mirror device **35** can prevent the mismatch between the wavefront of the pulsed laser beam **30** reflected from the mirror device **35** and the wavefront of the pulsed laser beam **30** having transmitted through the mirror device **35**.

In the first example of the mirror device **35**, the other configurations may be the same as the configurations of the beam splitter $\mathbf{321}a_k$ and the holder $\mathbf{321}d_k$ shown in FIG. **3**.

5.2 Second Example of the Mirror Device

Now, with reference to FIGS. **5**A and **5**B, the second example of the mirror device **35** will be described. FIG. **5**A is a drawing explaining the second example of the mirror device **35**. FIG. **5**B is a drawing explaining the flatness of each of the support member **352**, a first intermediate member **357**, and the optical element **350** shown in FIG. **5**A.

The second example of the mirror device **35** may have a configuration where the first intermediate member **357** is added to the first example of the mirror device **35**. The configuration of the second example of the mirror device **35**, which is the same as that of the first example of the mirror device **35** shown in FIGS. **4**A to **4**D, will not be described again here.

The first intermediate member **357** may be configured to adjust the surface accuracy of the support member **352** and the surface accuracy of the optical element **350**. The first intermediate member **357** may be a plate-like ring provided between the support member **352** and the optical element **350**. The inside diameter of the ring may be similar to the diameter of the through-hole **352***a* of the support member **352**. The outside diameter of the ring may be similar to the diameter of the optical element **350**. The first intermediate member **357** may be formed by using a metallic material or a ceramic material. The material for forming the first intermediate member **357** may be the same as the material for forming the support member **352**.

The first intermediate member **357** may be in surface contact with the first surface **350***a* of the optical element **350**. The flatness of a contact surface **357***a* of the first

intermediate member **357** in contact with the optical element **350** may be equal to or smaller than the flatness of the optical element **350**. The flatness of the contact surface **357***a* of the first intermediate member **357** may be equal to or smaller than the flatness of the first surface **350***a* of the optical element **350**. That is, the flatness of the contact surface **357***a* of the first intermediate member **357** in surface contact with the optical element **350** may be equal to or better than the flatness of the optical element **350**. By this means, the optical element **350** generating heat while being pushed against the support member **352** may thermally expand and shrink without being subjected to a locally applied force caused by the surface roughness and the irregularity of the contact surface **357***a* of the first intermediate member **357**.

The first intermediate member **357** may be in surface contact with the contact surface **352***f* of the support member **352**. The flatness of a contact surface **357***b* of the first intermediate member **357** in contact with the support member **352** may be equal to or smaller than the flatness of the optical element **350**, in the same way as the contact surface **357***a* of the first intermediate member **357**. The flatness of the contact surface **357***b* of the first intermediate member **357** may be equal to or smaller than the flatness of the first surface **350***a* of the optical element **350**. That is, the flatness of the contact surface **357***b* of the first intermediate member **357** in surface contact with the support member **352** may be equal to or better than the flatness of the optical element **350**.

If the flatness of the contact surface **357***b* of the first intermediate member **357** is not good, when the optical element **350** pushes the contact surface **357***a* by the pushing from the pushing members **353** or the thermal expansion, the contact surface **357***a* may be distorted according to the surface roughness and the irregularity of the contact surface **357***b*. Moreover, the contact thermal resistance between the first intermediate member **357** and the support member **352** may be increased, and therefore the heat may not be easy to be transferred from the first intermediate member **357** to the support member **352**. Then, a change in the volume of the optical element **350** may be increased due to the thermal expansion. In contrast, if the flatness of the contact surface **357***b* of the first intermediate member **357** is equal to or better than the flatness of the optical element **350**, the contact surface **357***a* may not be distorted according to the surface roughness and irregularity of the contact surface **357***b*. Moreover, the contact thermal resistance between the first intermediate member **357** and the support member **352** may be reduced, and therefore the heat may be easy to be transferred from the first intermediate member **357** to the support member **352**. Therefore, it is possible to reduce a change in the volume of the optical element **350** due to the thermal expansion. That is, when the flatness of the contact surface **357***b* of the first intermediate member **357** is equal to or better than the flatness of the optical element **350**, it is possible to prevent the optical element **350** from being distorted when the optical element **350** held by the holder **351** generates heat.

Here, according to the second example, a configuration of the holder **351** may be possible where the flatness of the contact surface **357***b* of the first intermediate member **357** is not equal to or better than the flatness of the optical element **350**. In this case, a buffering member such as soft metal or metallic paste (not shown) may fill a space between the contact surface **352***f* of the support member **352** and the contact surface **357***b* of the first intermediate member **357**. Examples of the soft metal may include indium, tin, silver, and copper. Examples of the metallic paste may include silver paste and copper paste. The buffering member may absorb the surface roughness and the irregularity of the contact surface **357***b* of the first intermediate member **357**. By this means, the contact surface **357***a* of the first intermediate member **357** in contact with the optical element **350** may not be distorted according to the surface roughness and the irregularity of the contact surface **357***b*. Moreover, the contact thermal resistance between the first intermediate member **357** and the support member **352** is reduced, and therefore the heat may be easy to be transferred from the first intermediate member **357** to the support member **352**. Therefore, it is possible to reduce a change in the volume of the optical element **350** due to the thermal expansion. Nevertheless, it is preferred that the flatness of the contact surface **357***b* of the first intermediate member **357** in contact with the support member **352** is equal to or better than the flatness of the optical element **350**.

With the above-described configuration according to the second example, even though the optical element **350** generating heat due to the absorption of the pulsed laser beam **30** is thermally expanded and shrunk by the cooling, the holder **351** can hold the optical element **350** without distorting the optical element **350**. Therefore, the second example of the mirror device **35** can prevent the optical element **350** from being distorted when the optical element **350** held by the holder **351** generates heat.

The other configuration of the second example of the mirror device **35** may be the same as the configuration of the first example of the mirror device **35** shown in FIGS. **4**A to **4**D.

5.3 Third Example of the Mirror Device

Now, with reference to FIGS. **6**A to **7**, the third example of the mirror device **35** will be described. FIG. **6**A is a drawing explaining the third example of the mirror device **35**. FIG. **6**B is a drawing explaining the flatness of each of the support member **352**, a second intermediate member **358**, and the optical element **350** shown in FIG. **6**A.

The third example of the mirror device **35** may have a configuration where the second intermediate member **358** is added to the first example of the mirror device **35**. The configuration of the third example of the mirror device **35**, which is the same as that of the first example of the mirror device **35** shown in FIGS. **4**A to **4**D, will not be described again here.

The second intermediate member **358** may be configured to be in surface contact with the optical element **350** to push the optical element **350** by the pushing members **353**. The second intermediate member **358** may be a plate-like ring provided between the pushing members **353** and the optical element **350**. The inside diameter of the ring may be similar to the diameter of the through-hole **354***c* of the fixing member **354**. The outside diameter of the ring may be similar to the diameter of the optical element **350**. The second intermediate member **358** may be formed by using a metallic material or a ceramic material. The material for forming the second intermediate member **358** may be the same as the material for forming the first intermediate member **357**.

The second intermediate member **358** may be in surface contact with the second surface **350***b* of the optical element **350**. The flatness of a contact surface **358***a* of the second intermediate member **358** in contact with the optical element **350** may be equal to or smaller than the flatness of the optical element **350**. The flatness of the contact surface **358***a* of the second intermediate member **358** may be equal to or smaller than the flatness of the second surface **350***b* of the optical element **350**. That is, the flatness of the contact surface **358***a* of the second intermediate member **358** in surface contact

with the optical element **350** may be equal to or better than the flatness of the optical element **350**.

The pushing members **353** may push the optical element **350** via the second intermediate member **358** in surface contact with the optical element **350**. Therefore, even in a case where the pushing members **353** are plunger screws, when the pushing members **353** push the optical element **350** via the second intermediate member **358**, a force is applied to the second surface **350***b* of the optical element **350** from the surface in contact with the second intermediate member **358**. Accordingly, the force applied to the optical element **350** when the pushing members **353** push the optical element **350** may not be concentrated on specified points pushed by the pushing members **353**, but distributed over the contact surface **358***a* of the second intermediate member **358**. Consequently, the stress generated in the optical element **350** by pushing the optical element **350** by the pushing members **353** may not be easy to be concentrated. Moreover, the flatness of the contact surface **358***a* of the second intermediate member **358** may be equal to or better than the flatness of the optical element **350**. The optical element **350** may be pushed by the pushing members **353** without being subjected to a locally applied force caused by the surface roughness and the irregularity of the contact surface **358***a*. By this means, according to the third example, even though the optical element **350** is pushed by the pushing members **353**, the holder **351** can hold the optical element **350** without distorting the optical element **350**. Therefore, the third example of the mirror device **35** can prevent the optical element **350** from being distorted when the optical element **350** held by the holder **351** generates heat.

FIG. **7** is a drawing explaining a modification of the third example of the mirror device **35**. The structure of the second intermediate member **358** of the modification of the third example of the mirror device **35** may be different from that of the second intermediate member **358** of the third example of the mirror device **35** shown in FIGS. **6**A and **6**B.

According to the modification of the third example, convex portions **358***b* may be provided on the second intermediate member **358**. The convex portions **358***b* may be provided on a surface **358***c* of the second intermediate member **358** in contact with the optical element **350**. The positions of the convex portions **358***b* on the surface **358***c* of the second intermediate member **358** may correspond to points on a surface **358***d* of the second intermediate member **358** pushed by the pushing members **353**. The top section of each of the convex portions **358***b* may be flat and constitute the contact surface **358***a* in contact with the optical element **350**. The top sections of the convex portions **358***b*, which constitute the contact surfaces **358***a*, may be in surface contact with the second surface **350***b* of the optical element **350** at the outer edge **350***c*. The convex portions **358***b* may be provided on at least three points, which correspond to the points pushed by the pushing members **353**, and are symmetric with respect to the center of the ring-shaped second intermediate member **358**. When the pushing members **353** are provided on the three points, three convex portions **358***b* may be provided on the surface **358***c* of the second intermediate member **358**. In addition, according to the modification of the third example, the pushing members **353** may be leaf springs, instead of the plunger screws. With the above-described configuration according to the modification of the third example, the size of the holder **351** may be smaller than that of the holder **351** according to the third example.

The other configuration of the third example of the mirror device **35** may be the same as the configuration of the first example of the mirror device **35** shown in FIGS. **4**A to **4**D.

5.4 Fourth Example of the Mirror Device

Now, with reference to FIG. **8**, the fourth example of the mirror device **35** will be described. FIG. **8** is a drawing explaining the fourth example of the mirror device **35**.

The flatness of the holder **351** of the fourth example of the mirror device **35** may be determined by the wavelength λ of the pulsed laser beam **30**. FIG. **8** shows a calculated simulation result of the diffraction limit of a laser beam on the reflective surface of an optical element which reflects part of the entering laser beam and transmits the other part of the laser beam therethrough, where the flatness of the reflective surface of the optical element is used as a parameter. In this simulation, the detailed steps for the calculation are as follows. First, making the laser beam which is a plane wave enter the optical element that reflects part of the entering laser beam and transmits the other part of the laser beam therethrough was performed. Next, focusing the laser beam reflected from the reflective surface of the optical element by using a perfect lens was performed. Then, calculating the radius of the reflected laser beam focused onto the focal point of the perfect lens, by using the flatness of the reflective surface of the optical element as a parameter was performed. The flatness of the reflective surface of the optical element is represented as a PV value, and is represented as a relative value with respect to the wavelength λ of the reflected laser beam.

The result of the calculation by this simulation is as follows. As shown in FIG. **8**, the focal radius of the reflected laser beam may be reduced within a range in which the flatness of the reflective surface of the optical element is smaller than the wavelength λ of the reflected laser beam. However, when the flatness of the reflective surface of the optical element is equal to or smaller than 0.18λ, the decrease in the focal radius of the reflected laser beam may be saturated. That is, when the flatness of the reflective surface of the optical element is 0.18λ (≈λ/5), the reflected laser beam from the reflective surface of the optical element may exhibit the diffraction limit. Therefore, if the flatness of the reflective surface of the optical element is equal to or smaller than 0.18λ (≈λ/5), the wavefront of the laser beam reflected from the reflective surface of the optical element may match the wavefront of the laser beam having transmitted through the optical element with high accuracy.

Moreover, when the flatness of the reflective surface of the optical element is equal to or smaller than 0.1λ (≈λ/10), the decrease in the focal radius of the reflected laser beam may be further saturated. Therefore, if the flatness of the reflective surface of the optical element is equal to or smaller than 0.1λ (≈λ/10), the wavefront of the laser beam reflected from the reflective surface of the optical element may match the wavefront of the laser beam having transmitted through the optical element with higher accuracy than when the flatness is 0.18λ (≈λ/5).

Based on the above-described result, the flatness of the optical element **350**, as a PV value, may be equal to or smaller than one-fifth of the wavelength λ of the pulsed laser beam **30** reflected from the optical element **350**. Preferably, the flatness of the optical element **350**, as a PV value, may be equal to or smaller than one-tenth of the wavelength λ of the pulsed laser beam **30** reflected from the optical element **350**. In addition, as described above, the flatness of the contact surface of the holder **351** in contact with the optical element **350** may be equal to or smaller than the flatness of the optical element **350**. Therefore, according to the fourth

example, the flatness of the contact surface of the holder **351** in contact with the optical element **350** may be equal to or smaller than one-fifth of the wavelength λ of the pulsed laser beam **30** reflected from the optical element **350**. Preferably, the flatness of the contact surface of the holder **351** in contact with the optical element **350** may be equal to or smaller than one-tenth of the wavelength λ of the pulsed laser beam **30** reflected from the optical element **350**. Therefore, the flatness of the holder **351** of the fourth example of the mirror device **35** may be equal to or smaller than one-fifth, preferably, one-tenth of the wavelength λ of the pulsed laser beam **30**.

The other configuration of the fourth example of the mirror device **35** may be the same as the first example of the mirror device **35** shown in FIGS. **4**A to **4**D.

6. EUV Light Generation Apparatus Including the Mirror Device

6.1 Configuration

Now, with reference to FIG. **9**, the EUV light generation apparatus **1** including the mirror device **35** will be described. FIG. **9** is a drawing explaining the EUV light generation apparatus **1** including the mirror device **35**. In FIG. **9**, the direction in which the EUV light **252** is outputted from the chamber **2** of the EUV light generation apparatus **1** to the exposure device **6** is defined as a Z-axis. An X-axis and a Y-axis are orthogonal to the Z-axis and are orthogonal to one another. The configuration of the EUV light generation apparatus **1** shown in FIG. **9**, which is the same as that of the EUV light generation apparatus **1** shown in FIG. **1**, will not be described again here. The configuration of the laser device **3** shown in FIG. **9**, which is the same as that of the laser device **3** shown in FIGS. **2** and **3**, will not be described again here. The configuration of the mirror device **35** shown in FIG. **9**, which is the same as that of the mirror device **35** shown in FIGS. **4**A to **8**, will not be described again here.

The laser device **3** used with the EUV light generation apparatus **1** shown in FIG. **9** may include a main pulse laser device **3***a* and a prepulse laser device **3***b*. The main pulse laser device **3***a* may include the laser controller **330**, the laser oscillator **301**, and the plurality of amplifiers **310**, in the same way as the laser device **3** shown in FIG. **2**. The wavelength of a laser beam outputted from the main pulse laser device **3***a* may be, for example, 10.6 μm. Laser beams outputted from the main pulse laser device **3***a* may be referred to as "main pulse laser beams **31***a* to **33***a*" in the same way as the description with reference to FIG. **1**. The prepulse laser device **3***b* may be a solid laser device such as a YAG laser. The wavelength of a laser beam outputted from the prepulse laser device **3***b* may be, for example, 1.06 μm. Laser beams outputted from the prepulse laser device **3***b* may be referred to as "prepulse laser beams **31***b* to **33***b*" in the same way as the main pulse laser beams **31***a* to **33***a*.

The prepulse laser beam may be a pulsed laser beam to be emitted to the target **27** before the main pulse laser beam is emitted to the target **27**. Upon being irradiated with the prepulse laser beam, the target **27** may be broken into a plurality of fine particles of the target **27**, and dispersed. The dispersed particles of the target **27** may improve the efficiency of generating EUV light by the main pulse laser beam. The dispersed particles of the target **27** resulting from irradiating the target **27** with the prepulse laser beam may be referred to as "secondary target." The other configuration of the laser device **3** shown in FIG. **9** may be the same as the configuration of the laser device **3** shown in FIGS. **2** and **3**.

The EUV light generation apparatus **1** shown in FIG. **9** may include the chamber **2**, a wavefront adjustment unit **371**, a wavefront adjustment unit **372**, a beam combiner **36**, and an EUV light generation control system **111**. The beam combiner **36** may include the mirror device **35**, a plate **361**, a high-reflection mirror **362**, a holder **363**, and a beam property measurement unit **364**. The EUV light generation control system **111** may include the EUV light generation controller **5**, a target controller **81**, and a delay circuit **82**.

The chamber **2** of the EUV light generation apparatus **1** may be formed into, for example, a hollow spherical shape or a hollow cylindrical shape. The direction of the central axis of the cylindrical chamber **2** may be the same as the direction in which the EUV light **252** is outputted to the exposure device **6**.

In the chamber **2**, a laser beam focusing optical system **22***a*, an EUV light focusing optical system **23***a*, the target collector **28**, a plate **225**, a plate **235**, and a moving stage **226** may be provided.

The plate **235** may be fixed to the inner side surface of the chamber **2**. A hole **235***a* that allows the pulsed laser beam **33** to pass therethrough may be formed at the center of the plate **235** in the thickness direction of the plate **235**. The opening direction of the hole **235***a* may be the same as the direction of the axis passing through the through-hole **24** and the plasma generation region **25** shown in FIG. **1**. The EUV light focusing optical system **23***a* may be provided on one surface of the plate **235**. Meanwhile, on the other surface of the plate **235**, the plate **225** may be provided via the moving stage **226**.

The EUV light focusing optical system **23***a* provided on the one surface of the plate **235** may include the EUV collector mirror **23** and a holder **231**. The holder **231** may hold the EUV collector mirror **23**. The holder **231** holding the EUV collector mirror **23** may be fixed to the plate **235**.

The plate **225** provided on the other surface of the plate **235** may be changed in its position and posture by the moving stage **226**. The moving stage **226** may move the plate **225** in three directions of X, Y, and Z. The moving stage **226** may be connected to the EUV light generation controller **5**. The moving stage **226** may move the plate **225** based on the control signal from the EUV light generation controller **5**. By this means, the position and the posture of the plate **225** may be changed. The laser beam focusing optical system **22***a* may be provided on the plate **225**.

The laser beam focusing optical system **22***a* may include the laser beam focusing mirror **22**, a holder **223**, and a holder **224**. The laser beam focusing mirror **22** may include an off-axis paraboloidal mirror **221** and a plane mirror **222**.

The holder **223** may hold the off-axis paraboloidal mirror **221**. The holder **223** holding the off-axis paraboloidal mirror **221** may be fixed to the plate **225**. The holder **224** may hold the plane mirror **222**. The holder **224** holding the plane mirror **222** may be fixed to the plate **225**.

The off-axis paraboloidal mirror **221** may be placed to face each of the window **21** provided on the bottom surface of the chamber **2** and the plane mirror **222**. The plane mirror **222** may be placed to face each of the hole **235***a* and the off-axis paraboloidal mirror **221**. The EUV light generation controller **5** may change the position and posture of the plate **225** via the moving stage **226**, so that it is possible to adjust the positions and postures of the off-axis paraboloidal mirror **221** and the plane mirror **222**. This adjustment may be performed such that the main pulse laser beam **33***a* and the prepulse laser beam **33***b*, which are reflected from the off-axis paraboloidal mirror **221** and the plane mirror **222**, are focused onto the plasma generation region **25**.

The target collector **28** may be located on the extension of the traveling direction of the target **27** outputted from the target supply part **26** into the chamber **2**.

In addition, the target supply part **26**, the droplet detector **41**, and an EUV light sensor **42** may be provided on the side surface of the chamber **2** shown in FIG. **9**. If the chamber **2** is formed into a hollow spherical shape, the target supply part **26**, the droplet detector **41**, and the EUV light sensor **42** may be provided on a wall surface of the chamber **2** where the window **21** and the connection part **29** are not provided.

The target supply part **26** may heat and melt the solid target **27**, and accommodate the molten target **27**. The target supply part **26** may form the droplet **271** from the accommodated target **27**, and supply the droplet **271** to the plasma generation region **25** in the chamber **2**. The direction in which the target supply part **26** outputs the droplet **271** may be orthogonal to the direction in which the EUV light **252** is outputted to the exposure device **6**. The target supply part **26** may be connected to the target controller **81**. The target supply part **26** may form the droplet **271** and supply the droplet **271** to the plasma generation region **25**, based on the control signal from the target controller **81**. The target supply part **26** may be placed on a movable stage (not shown). The movable stage may be connected to the target controller **81**. The movable stage may move the target supply part **26** such that the droplet **271** outputted into the chamber **2** reaches a targeted position, based on the control signal from the target controller **81**.

The droplet detector **41** may detect the droplet **271** outputted into the chamber **2**. The droplet detector **41** may detect the droplet **271** passing through a predetermined detection point between the target supply part **26** and the plasma generation region **25**. The droplet detector **41** may be connected to the target controller **81**. Upon detecting the droplet **271** passing through the detection point, the droplet detector **41** may output a droplet detection signal to the target controller **81**. The target controller **81** may determine whether or not the droplet **271** outputted from the target supply part **26** has passed through the detection point.

The EUV light sensor **42** may detect the EUV light **252** reflected from the EUV collector mirror **23**. The EUV light sensor **42** may be connected to the EUV light generation controller **5**. Upon detecting the EUV light **252** reflected from the EUV collector mirror **23**, the EUV light sensor **42** may calculate the optical properties of the EUV light **252**, such as the optical intensity and the pulse energy. The EUV light sensor **42** may output a measurement signal related to the optical properties of the EUV light **252** to the EUV light generation controller **5**. The EUV light generation controller **5** may determine whether or not the EUV light **252** reflected from the EUV collector mirror **23** has desired optical properties.

The wavefront adjustment unit **371** may adjust the wavefront of the main pulse laser beam **31***a*. The wavefront adjustment unit **371** may be a VRWM (variable radius wavefront mirror). The wavefront adjustment unit **371** may include a high-reflection mirror **371***a* and an actuator **371***b*. The high-reflection mirror **371***a* may be a deformable mirror. The high-reflection mirror **371***a* may be disposed to face the main pulse laser device **3***a* that emits the main pulse laser beam **31***a* and the high-reflection mirror **362** of the beam combiner **36**. The high-reflection mirror **371***a* may be inclined at an angle of 45 degrees with respect to the axis of the optical path of the main pulse laser beam **31***a*. The actuator **371***b* may change the curvature of the high-reflection mirror **371***a*. The actuator **371***b* may be disposed on the back side of the high-reflection mirror **371***a*. The actuator **371***b* may be connected to the EUV light generation controller **5**. The actuator **371***b* may change the curvature of the high-reflection mirror **371***a*, based on the control signal from the EUV light generation controller **5**. The wavefront of the main pulse laser beam **31***a* reflected from the high-reflection mirror **371***a* may be changed in accordance with the curvature of the high-reflection mirror **371***a*.

The wavefront adjustment unit **372** may adjust the wavefront of the prepulse laser beam **31***b*. The wavefront adjustment unit **372** may be a VRWM, like the wavefront adjustment unit **371**. The wavefront adjustment unit **372** may include a high-reflection mirror **372***a* and an actuator **372***b*, like the wavefront adjustment unit **371**. The high-reflection mirror **372***a* may be a deformable mirror. The high-reflection mirror **372***a* may be disposed to face the prepulse laser device **3***b* that emits the prepulse laser beam **31***b* and the mirror device **35** of the beam combiner **36**. The high-reflection mirror **372***a* may be inclined at an angle of 45 degrees with respect to the axis of the optical path of the prepulse laser beam **31***b*. The actuator **372***b* may change the curvature of the high-reflection mirror **372***a*. The actuator **372***b* may be disposed on the back side of the high-reflection mirror **372***a*. The actuator **372***b* may be connected to the EUV light generation controller **5**. The actuator **372***b* may change the curvature of the high-reflection mirror **372***a*, based on the control signal from the EUV light generation controller **5**. The wavefront of the prepulse laser beam **31***b* reflected from the high-reflection mirror **372***a* may be changed in accordance with the curvature of the high-reflection mirror **372***a*. Details of the wavefront adjustment units **371** and **372** will be described later with reference to FIGS. **11**A to **13**.

The beam combiner **36** may be an optical system configured to introduce the main pulse laser beam **31***a* and the prepulse laser beam **31***b* into the chamber **2** along approximately the same optical path axis. As described above, the beam combiner **36** may include the mirror device **35**, the plate **361**, the high-reflection mirror **362**, the holder **363**, and the beam property measurement unit **364**.

The plate **361** may be fixed to the bottom surface of the chamber **2** on the window **21** side. The holder **363** may hold the high-reflection mirror **362**. The holder **363** holding the high-reflection mirror **362** may be fixed to the plate **361** via a tilt stage (not shown). The tilt stage may be connected to the EUV light generation controller **5**. The tilt stage may move the holder **363** based on the control signal from the EUV light generation controller **5**. By this means, it is possible to change the position and posture of the high-reflection mirror **362** held by the holder **363**.

The high-reflection mirror **362** may be disposed to face the window **21** of the chamber **2** and the high-reflection mirror **371***a* of the wavefront adjustment unit **371**. The high-reflection mirror **362** may reflect the main pulse laser beam **31***a* outputted from the main pulse laser device **3***a* and reflected from the high-reflection mirror **371***a*, and guide the reflected main pulse laser beam **31***a* to the window **21**. The main pulse laser beam **32***a* reflected from the high-reflection mirror **362** may transmit through the mirror device **35** and the window **21**, and be introduced into the chamber **2**.

The mirror device **35** shown in FIG. **9** may be fixed to the plate **361**. The basic configuration of the mirror device **35** shown in FIG. **9** may be the same as that of the mirror device **35** shown in any one of FIGS. **4**A to **8**.

The optical element **350** of the mirror device **35** may be a dichroic mirror. The optical element **350** may be formed by using a diamond substrate. A reflection coating to highly reflect part of the prepulse laser beam **31***b* and to transmit part of the main pulse laser beam **31***a* therethrough may be applied to the first surface **350***a* of the optical element **350**. If the wavelength of the prepulse laser beam **31***b* is λp, the

flatness of the first surface **350***a* of the optical element **350** may be equal to or smaller than one-fifth of λp, preferably, one-tenth of λp. A reflection coating to highly reflect part of the main pulse laser beam **31***a* and to transmit part of the prepulse laser beam **31***b* therethrough may be applied to the second surface **350***b* of the optical element **350**. If the wavelength of the main pulse laser beam **31***a* is λm, the flatness of the second surface **350***b* of the optical element **350** may be equal to or smaller than one-fifth of λm, preferably, one-tenth of λm.

The mirror device **35** may be disposed such that the optical element **350** is located on the optical path of the prepulse laser beam **31***b* reflected from the high-reflection mirror **372***a* of the wavefront adjustment unit **372**. At the same time, the mirror device **35** may be disposed such that the optical element **350** is located on the optical path of the main pulse laser beam **32***a* reflected from the high-reflection mirror **362**. The mirror device **35** may be disposed such that the first surface **350***a* of the optical element **350** faces the window **21** of the chamber **2** and the high-reflection mirror **372***a* of the wavefront adjustment unit **372**. At the same time, the mirror device **35** may be disposed such that the second surface **350***b* of the optical element **350** faces the beam property measurement unit **364** and the high-reflection mirror **362**.

The optical element **350** of the mirror device **35** may reflect part of the prepulse laser beam **31***b* reflected from the high-reflection mirror **372***a* of the wavefront adjustment unit **372** and guide the reflected beam to the window **21**. At this time, the optical element **350** of the mirror device **35** may transmit part of the prepulse laser beam **31***b* reflected from the high-reflection mirror **372***a* of the wavefront adjustment unit **372** therethrough and guide the transmitted beam to the beam property measurement unit **364**. The optical element **350** of the mirror device **35** may reflect part of the main pulse laser beam **32***a* reflected from the high-reflection mirror **362** and guide the reflected beam to the beam property measurement unit **364**. At this time, the optical element **350** of the mirror device **35** may transmit part of the main pulse laser beam **32***a* reflected from the high-reflection mirror **362** therethrough and guide the transmitted beam to the window **21**. Here, the optical element **350** of the mirror device **35** may guide the main pulse laser beam **32***a* and the prepulse laser beam **32***b* to the window **21** along approximately the same optical path.

The holder **351** of the mirror device **35** may be the same as the holder **351** of the mirror device **35** shown in any of FIGS. **4**A to **8**. That is, although not shown in FIG. **9**, the holder **351** of the mirror device **35** may include the first intermediate member **357** or the second intermediate member **358**. The flatness of the contact surface **352***f* of the support member **352** of the holder **351** may be equal to or smaller than the flatness of the first surface **350***a* of the optical element **350**. That is, the flatness of the contact surface **352***f* of the support member **352** may be equal to or smaller than one-fifth of λp, preferably, one-tenth of λp. The other configuration of the mirror device **35** shown in FIG. **9** may be the same as that of the mirror device **35** shown in FIGS. **4**A to **8**.

The beam property measurement unit **364** may measure the beam properties of the main pulse laser beam **32***a* reflected from the mirror device **35** and the beam properties of the prepulse laser beam **32***b* having transmitted through the mirror device **35**. The beam property measurement unit **364** may include a dichroic mirror (not shown), a plurality of light focusing optical systems (not shown), and a plurality of two-dimensional image sensors (not shown). The dichroic mirror may split the main pulse laser beam **32***a* reflected from the mirror device **35** and the prepulse laser beam **32***b* having transmitted through the mirror device **35**. The plurality of light focusing optical systems may include a light focusing optical system configured to focus the main pulse laser beam **32***a* split by the dichroic mirror and a light focusing optical system configured to focus the prepulse laser beam **32***b* split by the dichroic mirror. The plurality of two-dimensional image sensors may include a two-dimensional image sensor configured to measure the beam properties of the main pulse laser beam **32***a* focused by the light focusing optical system, and a two-dimensional image sensor configured to measure the beam properties of the prepulse laser beam **32***b* focused by the light focusing optical system. Each of the plurality of two-dimensional image sensors may be connected to the EUV light generation controller **5**. The plurality of two-dimensional image sensors may generate measurement signals related to the measured beam properties of the main pulse laser beam **32***a* and the prepulse laser beam **32***b*, and output the signals to the EUV light generation controller **5**, respectively. The other configuration of the beam property measurement unit **364** shown in FIG. **9** may be the same as that of the beam property measurement unit $\mathbf{321}_k$ shown in FIGS. **2** and **3**.

As described above, the EUV light generation control system **111** may include the EUV light generation controller **5**, the target controller **81**, and the delay circuit **82**.

The EUV light generation controller **5** may send/receive various signals to/from an exposure device controller **61** which is the controller of the exposure device **6**. For example, the exposure device controller **61** may send an EUV light output command signal to command to output the EUV light **252**, to the EUV light generation controller **5**. The EUV light output command signal may contain information such as a targeted output timing, a targeted repetition frequency, and a targeted pulse energy of the EUV light **252**.

The EUV light generation controller **5** may totally control the whole operation of the EUV light generation system **11**, based on various signals sent from the exposure device **6**. The EUV light generation controller **5** may send/receive various control signals to/from the actuators of the tilt stage connected to the holder **363** and the moving stage **226**. By this means, the EUV light generation controller **5** may adjust the traveling directions of the main pulse laser beams **31***a* to **33***a* and the prepulse laser beams **31***b* to **33***b*, and the positions on which the main pulse laser beams **31***a* to **33***a* and the prepulse laser beams **31***b* to **33***b* are focused.

The EUV light generation controller **5** may send/receive various signals to/from the target controller **81**. By this means, the EUV light generation controller **5** may control the operations of the target supply part **26** and the droplet detector **41**. In particular, the EUV light generation controller **5** may output a target output command signal to command to output the target **27**, to the target controller **81**, based on the EUV light output command signal outputted from the exposure device controller **61**. The target output command signal may contain information such as a targeted output timing, a targeted output frequency, a targeted output position, a targeted velocity, and a targeted diameter of the target **27**.

The EUV light generation controller **5** may set a delay time in the delay circuit **82**, based on the EUV light output command signal outputted from the exposure device controller **61**. By this means, the EUV light generation controller **5** may control the timings at which the main pulse laser device **3***a* and the prepulse laser device **3***b* oscillate.

The EUV light generation controller **5** may control the operation of the wavefront adjustment unit **371**, based on the measurement signal related to the beam properties of the main pulse laser beam **32***a* outputted from the beam property measurement unit **364**. By this means, the EUV light generation controller **5** may adjust the wavefront of the main pulse laser beam **31***a* reflected from the high-reflection mirror **371***a* to a desired wavefront. The EUV light generation controller **5** may control the operation of the wavefront adjustment unit **372**, based on the measurement signal related to the beam properties of the prepulse laser beam **32***b* outputted from the beam property measurement unit **364**. By this means, the EUV light generation controller **5** may adjust the wavefront of the prepulse laser beam **31***b* reflected from the high-reflection mirror **372***a* to a desired wavefront. The EUV light generation controller **5** may control the operation of each of the components of the EUV light generation system **11**, based on the measurement signal related to the optical properties of the EUV light **252** outputted from the EUV light sensor **42**. Here, the hardware configuration of the EUV light generation controller **5** will be described later with reference to FIG. **10**.

The target controller **81** may control the output timing, the output frequency, the output position, the velocity, the diameter and so forth of the droplet **271** when the droplet **271** is outputted from the target supply part **26**, based on the target output command signal outputted from the EUV light generation controller **5**. The target controller **81** may be connected to the laser device **3** via the delay circuit **82**. The target controller **81** may output the droplet detection signal outputted from the droplet detector **41** directly to the delay circuit **82**. Here, the hardware configuration of the target controller **81** will be described later with reference to FIG. **10**.

The delay circuit **82** may output a trigger signal to the laser device **3** at a timing delayed by a predetermined delay time from when the droplet detection signal is outputted. The trigger signal outputted from the delay circuit **82** may be a signal to trigger the laser oscillation of the laser device **3** to output the pulsed laser beam **31**.

The trigger signal outputted from the delay circuit **82** may include a first trigger signal and a second trigger signal. The first trigger signal may be a signal to trigger the prepulse laser device **3***b* to output the prepulse laser beam **31***b*. The second trigger signal may be a signal to trigger the main pulse laser device **3***a* to output the main pulse laser beam **31***a*. The predetermined delay time set by the EUV light generation controller **5** may include a first delay time and a second delay time. The first delay time may determine the timing at which the first trigger signal is outputted to the prepulse laser device **3***b*. The first delay time may correspond to a period of time from when the droplet **271** passes through the above-described detection point until the droplet **271** reaches the plasma generation region **25**. The second delay time may determine the timing at which the second trigger signal is outputted to the main pulse laser device **3***a* after the first trigger signal is outputted. The second delay time may correspond to a period of time from when the droplet **271** reaching the plasma generation region **25** is irradiated with the prepulse laser beam **33***b* until the droplet **271** is dispersed and turned into a secondary target. By this means, when the droplet **271** having passed through the above-described detection point between the target supply part **26** and the plasma generation region **25** reaches the plasma generation region **25**, the droplet **271** may be irradiated with the prepulse laser beam **33***b*. Then, the secondary target generated by the irradiation with the prepulse laser beam **33***b* may be irradiated with the main pulse laser beam **33***a*.

The other configuration of the EUV light generation apparatus **1** shown in FIG. **9** may be the same as that of the EUV light generation apparatus **1** shown in FIG. **1**.

6.2 Operation

After activating the EUV light generation apparatus **1**, the EUV light generation controller **5** may set the first delay time and the second delay time in the delay circuit **82**. By this means, it is possible to set the timing at which the droplet **271** reaching the plasma generation region **25** is irradiated with the prepulse laser beam **33***b*, and the timing at which the secondary target is irradiated with the main pulse laser beam **33***a*. The EUV light generation controller **5** may receive the EUV light output command signal sent from the exposure device **6**. The EUV light generation controller **5** may output the target output command signal to the target controller **81**, based on the EUV light output command signal.

The target controller **81** may control the operation of each of the components of the target supply part **26**, based on the target output command signal. The target supply part **26** may output the droplet **271** which satisfies various targeted values contained in the target output command signal, into the chamber **2**, according to the control from the target controller **81**. When the droplet **271** passes through the above-described detection point in the chamber **2**, the droplet detector **41** may output the droplet detection signal, and the droplet detection signal may be inputted to the delay circuit **82** via the target controller **81**.

The delay circuit **82** may output the first trigger signal to the prepulse laser device **3***b* at a timing which is delayed by the first delay time from when the droplet detection signal is outputted. Upon receiving the first trigger signal, the prepulse laser device **3***b* may output the prepulse laser beam **31***b*. The prepulse laser beam **31***b* may travel through the wavefront adjustment unit **372**, the mirror device **35**, and the laser beam focusing optical system **22***a* in this order, and be focused onto the plasma generation region **25** as the prepulse laser beam **33***b*. The droplet **271** may be irradiated with the prepulse laser beam **33***b* in synchronization with the timing at which the droplet **271** reaches the plasma generation region **25**. The droplet **271** irradiated with the prepulse laser beam **33***b* may be broken and dispersed, and therefore turned into the secondary target.

The delay circuit **82** may output the second trigger signal to the main pulse laser device **3***a* at a timing which is delayed by the second delay time from when the first trigger signal is outputted. Upon receiving the second trigger signal, the main pulse laser device **3***a* may output the main pulse laser beam **31***a*. The main pulse laser beam **31***a* may travel through the wavefront adjustment unit **371**, the high-reflection mirror **362**, the mirror device **35**, and the laser beam focusing optical system **22***a* in this order, and be focused onto the plasma generation region **25** as the main pulse laser beam **33***a*. The secondary target may be irradiated with the main pulse laser beam **33***a* in synchronization with the timing at which the secondary target is generated in the plasma generation region **25**. The secondary target irradiated with the main pulse laser beam **33***a* may be turned into plasma and emit light containing the EUV light **251**.

When the main pulse laser beam **31***a* and the prepulse laser beam **31***b* enter the mirror device **35**, the optical element **350** of the mirror device **35** held by the holder **351** may generate heat due to the absorption of the main pulse laser beam **31***a* and the prepulse laser beam **31***b*. The heat

generated in the optical element **350** may be transferred to the support member **352** in surface contact with the optical element **350**. The heat transferred to the support member **352** may be transferred to the refrigerant circulating through the flow channel **352***b*, and discharged to the outside of the mirror device **35**. The holder **351** may hold the optical element **350** by applying a force uniformly to the optical element **350** without restricting the thermal expansion and shrinkage of the optical element **350**. In addition, the holder **351** may hold the optical element **350** thermally expanding and shrinking, without locally applying a force caused by the surface roughness and the irregularity of the contact surface **352***f*. Moreover, the holder **351** may reduce a change in the volume of the optical element **350** due to the thermal expansion. Therefore, it is possible to prevent the optical element **350** from being distorted due to the heat generated in the optical element **350** held in the holder **351**. By this means, the wavefront of the prepulse laser beam **32***b* reflected from the optical element **350** may match the wavefront of the prepulse laser beam **32***b* having transmitted through the optical element **350**. The wavefront of the main pulse laser beam **32***a* reflected from the optical element **350** may match the wavefront of the main pulse laser beam **32***a* having transmitted through the optical element **350**.

The main pulse laser beam **32***a* reflected from the optical element **350** and the prepulse laser beam **32***b* having transmitted through the optical element **350** may enter the beam property measurement unit **364**. The beam property measurement unit **364** may measure the beam properties, including the beam divergence, of the received main pulse laser beam **32***a* and prepulse laser beam **32***b*. The beam property measurement unit **364** may generate measurement signals related to the measured beam properties of the main pulse laser beam **32***a* and the prepulse laser beam **32***b*, and output the signals to the EUV light generation controller **5**.

The EUV light generation controller **5** may control the operations of the wavefront adjustment unit **371** and the wavefront adjustment unit **372**, based on the measurement signals related to the beam properties of the main pulse laser beam **32***a* and the prepulse laser beam **32***b*, which are outputted from the beam property measurement unit **364**. By this means, the EUV light generation controller **5** may adjust the wavefront of each of the main pulse laser beam **31***a* and the prepulse laser beam **31***b* to a desired wavefront.

6.3 Effect

The EUV light generation apparatus **1** including the mirror device **35** can match the axis of the optical path of the main pulse laser beam **32***a* to the axis of the optical path of the prepulse laser beam **32***b*. The EUV light generation apparatus **1** including the mirror device **35** can prevent the optical element **350** held by the holder **351** from being distorted when the optical element **350** generates heat. The EUV light generation apparatus **1** including the mirror device **35** can prevent the wavefront of each of the main pulse laser beam **32***a* and the prepulse laser beam **32***b* reflected from the optical element **350**, from being changed due to the distortion of the optical element **350**. Therefore, the EUV light generation apparatus **1** including the mirror device **35** can focus the main pulse laser beam **33***a* and the prepulse laser beam **33***b* having the desired beam properties onto the plasma generation region **25**. By this means, the EUV light generation apparatus **1** including the mirror device **35** can generate the stable EUV light **252**.

7. Others

7.1 Hardware Environment of Each Controller

A person skilled in the art would understand that the subject matters disclosed herein can be implemented by combining a general purpose computer or a programmable controller with a program module or a software application. In general, the program module includes routines, programs, components and data structures which can execute the processes disclosed herein.

FIG. **10** is a block diagram showing an exemplary hardware environment in which various aspects of the subject matters disclosed herein can be implemented. An exemplary hardware environment **100** shown in FIG. **10** may include a processing unit **1000**, a storage unit **1005**, a user interface **1010**, a parallel I/O controller **1020**, a serial I/O controller **1030**, and an A/D, D/A converter **1040**, but the configuration of the hardware environment **100** is not limited to this.

The processing unit **1000** may include a central processing unit (CPU) **1001**, a memory **1002**, a timer **1003**, and a graphics processing unit (GPU) **1004**. The memory **1002** may include a random access memory (RAM) and a read only memory (ROM). The CPU **1001** may be any of commercially available processors. A dual microprocessor or another multiprocessor architecture may be used as the CPU **1001**.

The components shown in FIG. **10** may be interconnected with each other to perform the processes described herein.

During its operation, the processing unit **1000** may read and execute a program stored in the storage unit **1005**, read data together with the program from the storage unit **1005**, and write data to the storage unit **1005**. The CPU **1001** may execute a program read from the storage unit **1005**. The memory **1002** may be a work area in which a program executed by the CPU **1001** and data used in the operation of the CPU **1001** are temporarily stored. The timer **1003** may measure a time interval and output the result of the measurement to the CPU **1001** according to the execution of the program. The GPU **1004** may process image data according to a program read from the storage unit **1005**, and output the result of the process to the CPU **1001**.

The parallel I/O controller **1020** may be connected to parallel I/O devices that can communicate with the processing unit **1000**, such as the exposure device controller **61**, the EUV light generation controller **5**, the controller **323**, the laser controller **330**, the two-dimensional image sensor **321***c*, the two-dimensional image sensors for the beam property measurement unit **364**, the target controller **81**, and the delay circuit **82**. The parallel I/O controller **1020** may control the communication between the processing unit **1000** and those parallel I/O devices. The serial I/O controller **1030** may be connected to serial I/O devices that can communicate with the processing unit **1000**, such as the actuator **371***b*, the actuator **372***b*, the moving stage **226**, the target supply part **26**, the water pressure adjustment unit, and the pulse motor. The serial I/O controller **1030** may control the communication between the processing unit **1000** and those serial I/O devices. The A/D, D/A converter **1040** may be connected to analog devices such as the temperature sensor, the pressure sensor, the voltage sensor, various sensors for a vacuum gauge, the target sensor **4**, the droplet detector **41** and the EUV light sensor **42** via analog ports, may control the communication between the processing unit **1000** and those analog devices, and may perform A/D, D/A conversion of the contents of the communication.

The user interface **1010** may present the progress of the program executed by the processing unit **1000** to an operator, in order to allow the operator to command the processing unit **1000** to stop the program and to execute an interruption routine.

The exemplary hardware environment **100** may be applicable to the exposure device controller **61**, the EUV light

generation controller **5**, the controller **323**, the laser controller **330**, and the target controller **81** in the present disclosure. A person skilled in the art would understand that those controllers may be realized in a distributed computing environment, that is, an environment in which tasks are performed by the processing units connected to each other via a communication network. In this disclosure, the exposure device controller **61**, the EUV light generation controller **5**, the controller **323**, the laser controller **330**, and the target controller **81** may be connected to each other via a communication network such as Ethernet or Internet. In the distributed computing environment, the program module may be stored in both of a local memory storage device and a remote memory storage device.

7.2 Wavefront Adjustment Unit

With reference to FIGS. **11**A to **13**, the configuration of the wavefront adjustment units **371** and **372** will be described. The wavefront adjustment units **371** and **372** may have the same configuration, and therefore the wavefront adjustment unit **371** will be described as an example. FIG. **11**A is a drawing explaining the configuration of the wavefront adjustment unit **371**, where the laser beam entering the wavefront adjustment unit **371** is a plane wave. FIG. **11**B is a drawing explaining the configuration of the wavefront adjustment unit **371**, where the laser beam entering the wavefront adjustment unit **371** is a convex wave. FIG. **11**C is a drawing explaining the configuration of the wavefront adjustment unit **371**, where the laser beam entering the wavefront adjustment unit **371** is a concave wave.

As described above, the wavefront adjustment unit **371** may be a VRWM. The VRWM may be an element configured to transform a plane wave into a concave wave or a convex wave having a curved wavefront. To the contrary, the VRWM may transform a concave wave or a convex wave having a curved wavefront into a plane wave. In addition, the VRWM may be an element configured to adjust the curvature of the wavefront of a concave wave or a convex wave to a different curvature. As described above, the wavefront adjustment unit **371** may include the high-reflection mirror **371***a*, and the actuator **371***b* configured to change the curvature of the high-reflection mirror **371***a*.

When the laser beam entering the wavefront adjustment unit **371** is a plane wave, the actuator **371***b* may adjust the curvature of the high-reflection mirror **371***a* to maintain the reflective surface of the high-reflection mirror **371***a* to be a flat surface. Meanwhile, when the laser beam entering the wavefront adjustment unit **371** is a convex wave, the actuator **371***b* may adjust the curvature of the high-reflection mirror **371***a* such that the reflective surface of the high-reflection mirror **371***a* becomes a concave surface. When the laser beam entering the wavefront adjustment unit **371** is a concave wave, the actuator **371***b* may adjust the curvature of the high-reflection mirror **371***a* such that the reflective surface of the high-reflection mirror **371***a* becomes a convex surface. By this means, the laser beam reflected from the high-reflection mirror **371***a* shown in FIGS. **11**A to **11**C may become a plane wave.

FIG. **12** is a drawing explaining the actuator **371***b* of the wavefront adjustment unit **371** shown in FIGS. **11**A to **11**C. The actuator **371***b* may include a pressure applying member and a water pressure adjustment unit. The pressure applying member may apply pressure to the high-reflection mirror **371***a* from the back side of the high-reflection mirror **371***a*, depending on the water pressure supplied from the water pressure adjustment unit. The water pressure adjustment unit may regulate the water pressure supplied to the pressure applying member. The water pressure adjustment unit may regulate the water pressure supplied to the pressure applying member to adjust the amount of the pressure applied to the high-reflection mirror **371***a*, based on the control signal from the EUV light generation controller **5**. By this means, the actuator **371***b* shown in FIG. **12** may change the curvature of the high-reflection mirror **371***a*.

With reference to FIG. **13**, another example of the configuration of the wavefront adjustment unit **371** will be described. FIG. **13** is a drawing explaining another example of the configuration of the wavefront adjustment unit **371**. The wavefront adjustment unit **371** may include an off-axis paraboloidal convex mirror, an off-axis paraboloidal concave mirror, a high-reflection mirror **1**, a high-reflection mirror **2**, a single axis stage, a pulse motor, and holders. The off-axis paraboloidal convex mirror, the off-axis paraboloidal concave mirror, the high-reflection mirror **1**, and the high-reflection mirror **2** may be held by the holders, respectively. A flow channel (not shown) through which the refrigerant flows may be provided in each of the holders.

The off-axis paraboloidal convex mirror, the off-axis paraboloidal concave mirror, the high-reflection mirror **1**, and the high-reflection mirror **2** may be disposed to be inclined at 45 degrees with respect to the axes of the optical paths of the laser beams entering the off-axis paraboloidal convex mirror, the off-axis paraboloidal concave mirror, the high-reflection mirror **1**, and the high-reflection mirror **2**, respectively. The off-axis paraboloidal convex mirror and the off-axis paraboloidal concave mirror are disposed such that their focusing points match with one another. The off-axis paraboloidal convex mirror may enlarge the diameter of the laser beam having entered the wavefront adjustment unit **371**. The off-axis paraboloidal concave mirror may collimate the laser beam enlarged by the off-axis paraboloidal convex mirror. The high-reflection mirrors **1** and **2** may change the axis of the optical path of the laser beam collimated by the off-axis paraboloidal concave mirror to the extension of the axis of the optical path of the laser beam entering the off-axis paraboloidal convex mirror. By this means, the wavefront adjustment unit **371** shown in FIG. **13** may match the axis of the optical path of the laser beam exiting the wavefront adjustment unit **371** to the axis of the optical path of the laser beam entering the wavefront adjustment unit **371**.

The off-axis paraboloidal concave mirror and the high-reflection mirror **1** may be placed on the single axis stage. The single axis stage may be driven by the pulse motor, and change the distance between the off-axis paraboloidal concave mirror and the off-axis paraboloidal convex mirror, and the distance between the high-reflection mirror **1** and the high-reflection mirror **2**. The pulse motor may adjust the amount of the movement of the single axis stage, based on the control signal from the EUV light generation controller **5**. If the distance between the off-axis paraboloidal concave mirror and the off-axis paraboloidal convex mirror, that is, the distance between the high-reflection mirror **1** and the high-reflection mirror **2** is changed, the wavefront of the laser beam exiting the wavefront adjustment unit **371** may be changed with respect to the wavefront of the laser beam entering the wavefront adjustment unit **371**. By this means, the wavefront adjustment unit **371** shown in FIG. **13** may adjust the wavefront of the laser beam entering the wavefront adjustment unit **371**.

All the optical elements included in the wavefront adjustment unit **371** shown in FIG. **13** may be reflective optical elements, and held by the holders each including a flow channel through which the refrigerant flows. Therefore, even when receiving a high-power laser beam of, for example, 5

kW to 40 kW, the wavefront adjustment unit **371** may stably adjust the wavefront of the laser beam. Here, the off-axis paraboloidal concave mirror of the wavefront adjustment unit **371** shown in FIG. **13** may be replaced with the high-reflection mirror **1** or the high-reflection mirror **2**, if the focusing point of the off-axis paraboloidal concave mirror matches the focusing point of the off-axis paraboloidal convex mirror. The wavefront adjustment unit **371** shown in FIG. **13** may employ two off-axis paraboloidal concave mirrors, instead of the off-axis paraboloidal convex mirror and the off-axis paraboloidal concave mirror.

7.3 Modification

It would be obvious to a person skilled in the art that the technologies described in the above-described embodiments including the modifications may be compatible with each other.

The descriptions above are intended to be illustrative only and the present disclosure is not limited thereto. Therefore, it will be apparent to those skilled in the art that it is possible to make modifications to the embodiments of the present disclosure within the scope of the appended

The terms used this specification and the appended claims should be interpreted as "non-limiting." For example, the terms "include" and "be included" should be interpreted as "including the stated elements but not limited to the stated elements," The term "have" should be interpreted as "having the stated elements but not limited to the stated elements." Further, the indefinite art "a/an" should be interpreted as "at least one" or "one or more."

REFERENCE SIGNS LIST

1 EUV light generation apparatus
27 target
301 laser oscillator
310 amplifier
35 mirror device
350 optical element
350*a* first surface
350*b* second surface
351 holder
352 support member
352*b* flow channel
352*f* contact surface
353 pushing member
357 first intermediate member
357*a* contact surface
358 second intermediate member

The invention claimed is:

1. A mirror device comprising:

an optical element configured to reflect part of a laser beam and transmit the other part of the laser beam therethrough; and

a holder in surface contact with the optical element to hold the optical element,

wherein a flatness of a contact surface of the holder in contact with a first surface of the optical element is equal to or smaller than a flatness of the first surface of the optical element, and

wherein the holder includes:

a support member having the contact surface in surface contact with the first surface of the optical element to support the optical element; and

a pushing member configured to push the optical element against the support member by pushing a second surface of the optical element.

2. The mirror device according to claim **1**, wherein:

the holder further includes a first intermediate member disposed between the support member and the first surface, the first intermediate member being in surface contact with the support member and the first surface; and

a flatness of a contact surface of the first intermediate member in contact with the first surface is equal to or smaller than the flatness of the first surface.

3. The mirror device according to claim **2**, wherein a flatness of a contact surface of the first intermediate member in contact with the support member is equal to or smaller than the flatness of the first surface.

4. The mirror device according to claim **1**, wherein:

the holder further includes a second intermediate member disposed between the pushing member and the second surface, the second intermediate member being in surface contact with the second surface; and

the pushing member pushes the second surface via the second intermediate member.

5. The mirror device according to claim **1**, wherein a flow channel through which a refrigerant flows is provided in the support member.

6. The mirror device according to claim **1**, wherein the pushing member pushes at least three points of the second surface.

7. The mirror device according to claim **1**, wherein the laser beam is emitted from an amplifier that amplifies a seed beam, or a laser oscillator.

8. The mirror device according to claim **1**, wherein the laser beam is emitted to a target, so that the target is turned into plasma to generate extreme ultraviolet light.

9. A mirror device comprising:

an optical element configured to reflect part of a laser beam and transmit the other part of the laser beam therethrough; and

a holder in surface contact with the optical element to hold the optical element,

wherein, when a wavelength of the laser beam reflected from a surface of the optical element is λ, a flatness of a contact surface of the holder in contact with the optical element is equal to or smaller than one-fifth of λ.

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